THE STUDENT'S HANDBOOK OF PHYSICAL GEOLOGY.

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Israel C. Russell
Ann Arbor Mich
Jan. 1893.

THE STUDENT'S HANDBOOK

OF

PHYSICAL GEOLOGY.

BY

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OF THE GEOLOGICAL SURVEY OF ENGLAND AND WALES.

With numerous Diagrams and Illustrations.

SECOND EDITION, REVISED.

LONDON:

GEORGE BELL & SONS, YORK ST., COVENT GARDEN,

AND NEW YORK.

1892.

CHISWICK PRESS:—C. WHITTINGHAM AND CO., TOOKS COURT,
CHANCERY LANE.

PREFACE.

As stated in the Preface to the First Edition of this treatise, my aim in writing it was to supply a handbook of Geology at a moderate price, and in a form that was specially adapted for teaching purposes; a book with which every member of a geological class could provide himself, and one upon which the teacher could readily build up a superstructure of further geological knowledge.

A text-book of geology must necessarily be chiefly occupied in presenting known facts and phenomena, and in describing suitable instances or illustrations of them, but its value for educational purposes must greatly depend upon its plan or system of arrangement, and upon the manner in which its contents are presented to the reader. The general arrangement in this volume is that which has always seemed to me the most natural and the best fitted for the gradual development of the subject. Dry details respecting minerals and rocks are apt to discourage the young student if he is obliged to master them before coming to the descriptive branches of geology.

The arrangement of the matter in each chapter has also been considered, for unless the writer or lecturer forms for himself a clear idea of what he is going to say on each separate subject, he cannot hope to make it clear to his readers or hearers.

Physiographical Geology now takes rank as a primary

division of the subject, and its natural place in a text-book seems to be immediately after the sections on Dynamical and Structural Geology. I agree with Mr. G. K. Gilbert of the U. S. Geological Survey, who says, "starting from geological agencies as data, we may proceed in one direction to the development of geological history, or in another to the explanation of terrestrial scenery and topography, and if the development of the earth's history is the peculiar theme of geology, it follows that the explanation of topography or physiographical geology is of the nature of an incidental result,—a sort of corollary to dynamical geology."

This volume includes only the three branches of the subject mentioned above, those of Palæontological and Historical Geology being left to form another volume.

At the time the First Edition was written there were certain subjects which it was necessary to treat with much caution, but during the last few years much light has been thrown on the questions of Metamorphism, Mountain-building, and the substructure of the Earth's crust, so that more definite and detailed information can now be placed before the reader. Other portions of the work also required fuller treatment, so that the volume has been expanded by more than a hundred pages, and the number of illustrations has been correspondingly increased. Indeed so much has been added or re-written, that this edition is almost a new book, but the same arrangement of subjects has been preserved.

In preparing this edition I have spared no pains to make it a reliable handbook for those branches of the science which it embraces, and I have to thank many friends for assisting me in this object. To Professor Bonney and Rev. O. Fisher my thanks are especially due for aid and information regarding the subjects which are particularly their own, and to Professor Bonney I am also

indebted for many hints and corrections made on the proofs of the second half of the book, which he was kind enough to read. For the revision of the chapters on Igneous Rocks I am responsible, but the alterations have Professor Bonney's approbation; and most of what was written by him for the first edition has been incorporated.

Most of the diagrams have been drawn by myself; of the other illustrations, some have been taken from Dr. Mantell's works, and others, including the frontispiece, from Professor Bonney's "Alpine Regions," by permission of the author and publishers. Additional views have been obtained for this edition from Messrs. Cassell, and from the publishers of the "Pictorial Itinerary of North Wales" (Woodall and Co., Oswestry).

In conclusion, I need only add that I shall feel grateful for any criticisms or suggestions that may lead to the improvement of the work, should a third edition be called for.

A. J. JUKES-BROWNE.

March, 1892.

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INTRODUCTION.

DEFINITIONS are never easy, and it is especially difficult to frame an accurate definition of Geology, because it is not easy to limit the scope of its application. Two different definitions of the science may indeed be given; one describing it in a broad and comprehensive sense, the other dealing only with its more special and restricted meaning.

Regarded from the wider point of view, Geology is not so much one separate science as the application of all the physical sciences to the examination and elucidation of the structure of the earth. Mr. Jukes has well observed[1] "that we might without impropriety regard all the physical sciences as included under two great heads, namely, astronomy and geology; the one comprehending all those sciences which teach us the constitution, the motions, the relative places, and the mutual actions of the astra, or heavenly bodies; while the other would include all the sciences which deal with the phenomena presented by the one astrum on which we live, and investigate the nature and distribution both of the inorganic matter of the globe, and of the living beings which inhabit it."

The truth of this large and comprehensive view of geology is shown by the very fact of its late appearance in the world of science. The crude ideas regarding the structure and history of the earth, and the nature of fossils which were prevalent in the seventeenth and eighteenth centuries, cannot be dignified by the name of geology. The *Geognosy*, taught by Werner in the latter part of the eighteenth century, was little more than a special branch

[1] "Student's Manual of Geology," p. 1.

of mineralogy; and Desmarest, though an opponent of Werner's views regarding the origin of rocks, treated of geology under the head of physical geography.

It was not, indeed, until much progress had been made in all the physical sciences that geology could possess any solid foundation or any real scientific status. It was not until chemists were able to explain the true nature of the mineral substances which enter into the composition of rocks; until geographers had explored the surface of the earth, and natural philosophers had described the phenomena of volcanoes and earthquakes, rivers and glaciers, tides and currents; until biologists had described and classified the greater number of existing animals and plants —it was not until all these essential data had been collected and studied that the geologist could realize the processes and operations by which rocks were formed, or could utilize his discoveries of the fossil organisms which they enclose.

This necessary knowledge was not possessed by anyone before the beginning of the present century, and, consequently, before this era there was no true science of geology. Hutton's knowledge of chemistry and mineralogy was considerable, and his powers of observation and generalization were truly remarkable, but his lack of information in respect to other sciences necessarily caused his "Theory of the Earth" to be a very imperfect view. It was not till 1790 that the foundations of geology were laid, when William Smith began to establish the two great principles which have caused him to be known as the father of the science, viz., the superposition of stratified rocks, and the identification of strata by their fossil contents; ever since that time materials have been rapidly accumulating for the construction of a true outline of the history of the earth, so far as it can be learnt from a study of the rocks that compose its crust.

It does not follow from what has just been said that every individual geologist must possess a great and accurate knowledge of the whole circle of physical sciences; it is only necessary that this knowledge should exist, and be readily accessible, so that the geologist can combine the results obtained by other sciences with his own special observations, and apply them to the solution of the many

difficult problems which arise in the course of his researches.

Here the reader may well ask, what are the special observations which the geologist makes, and what is it which he regards as his special business? If the wide scope already indicated be properly given to geology, and if it claims assistance from every other science which treats of anything belonging to the earth; what is it which the geologist teaches to the students of these other sciences in return for the knowledge communicated to him?

The answer to these questions will show that geology has a more limited and applied meaning, which may be defined as follows. Geology in this sense is the application of the knowledge gained by the study of the existing state of things to the elucidation of the past history of the earth. The geologist takes the information gained by others regarding the operations that are now in action on the surface of the globe, and uses this knowledge to explain the results of the operations which have taken place in the past. In this way he is able to explain the manner in which the various rocks have been formed, and the processes by which they have acquired their distinctive characters and their relative positions.

The constitution of the crust of the earth, and the history of its formation, are thus the special objects of his study and research, and, as Mr. Jukes observed, the collection and co-ordination of the facts on which this history is founded is the proper and peculiar business of the geologist: "the ditch, the cutting, the quarry, the mine, the cliff, the gully, the river-bank, and the mountain-side, are his *subjects*, which he has to examine and dissect." From the indications observed in all natural and artificial excavations, he must make out the internal structure or solid geometry of every district, and note all the facts which will enable him to explain the geological history of each natural province or area, until all the accessible portions of the earth's crust have been explored and described, and the "record of the rocks" has been read from beginning to end.

A beginner would probably suppose that in order to pursue the task of investigating the solid structure of the

earth, it would only be necessary to become acquainted with the nature and origin of the rocky matters of which it is composed, and that there would be no occasion for studying the forms of animals and plants. The fact is, however, that an acquaintance with organic remains, as they occur in a fossil state, is even more necessary for a geologist than a knowledge of inorganic substances.

The cause of this necessity may be briefly stated as follows. When portions of the earth's crust came to be examined, it was found that the various rocks of which it was composed were arranged in a regular series, the several rock-groups having been formed one after the other during successive periods, each of long duration. Now, the mineral substances produced during any one of this vast succession of ages do not appear to differ essentially from those formed under like circumstances at another time. We cannot, therefore, with any certainty discover the order of time in which the series of rocks was formed, or their original order of superposition, from an examination of their mineral characters only. The animals and plants, however, which lived at any one period of the earth's history were different from those which lived at other periods. There has been a constant succession of living beings on the earth, different races, species, and genera following each other in a regular order, and when that order has once been ascertained it is clear that any rock containing fossil remains can be assigned to its proper place in the geological series.

There are few formations that are entirely destitute of fossils, and in districts where the relative position of the rock-groups is for any cause obscure, or where their original order has been disarranged by the subsequent action of disturbing forces, it is chiefly by aid of their fossil contents that their true succession and superposition can be satisfactorily determined.

Practically it has been found that while an acquaintance with the characters of some twenty or thirty of the commoner minerals is all that a geologist must necessarily learn of mineralogy, the number of animals and plants, with the forms and names of which he will have to make himself familiar, must be reckoned by hundreds.

From the foregoing remarks it will be seen that before

we can properly understand the appearances presented by the rocks which compose the crust of the earth, we must have some knowledge of the agencies by which rocks are now being formed, and by which the form of the earth's surface is being modified. Again, before we can attempt to construct any history of the formation of the earth's crust we must be acquainted with the leading facts and conclusions of Palæontology, as that branch of the science is termed which deals with the structure and classification of former existences.

Descriptions of the various natural operations which are now in progress upon the earth, and of the changes which they bring about, were aptly termed by Sir Charles Lyell, "the Principles of Geology"; since it is only by a careful study of the changes which are taking place in the present that we can hope to interpret the many changes which have taken place in the past.

A knowledge of these first principles ought, therefore, to form the groundwork or introduction to the study of those subjects which are, perhaps, the more special province of geological science.

It seems, then, the most natural and logical treatment of the subject in the first place to describe the geological processes which can be seen at work in various parts of the world, and to show the student how these operations will explain the facts observable in the crust of the earth, and how they will account for the diversified features which its surface presents. By these steps we can proceed to the history of the earth since it became a habitable globe, as interpreted by means of the observations and deductions previously arrived at. This treatise, therefore, will be divided into five parts, which may be designated and defined as follow.

1. *Dynamical Geology.*—An account of the actual results produced by the geological agencies now in operation.

2. *Geognosy, or Structural Geology.*—Being the study of rocks and rock-masses, without reference to the geological time of their production. This branch may be divided into two sections: *a. Petrology*—the study of the mineral components of rocks as visible in detached specimens. *b. Tectonic Geology*—the study of rock-masses; their struc-

tural characters, and mutual relations, as visible in the earth.

3. *Physiography.*—An explanation of the origin of hills and valleys, lakes, escarpments, and mountains.

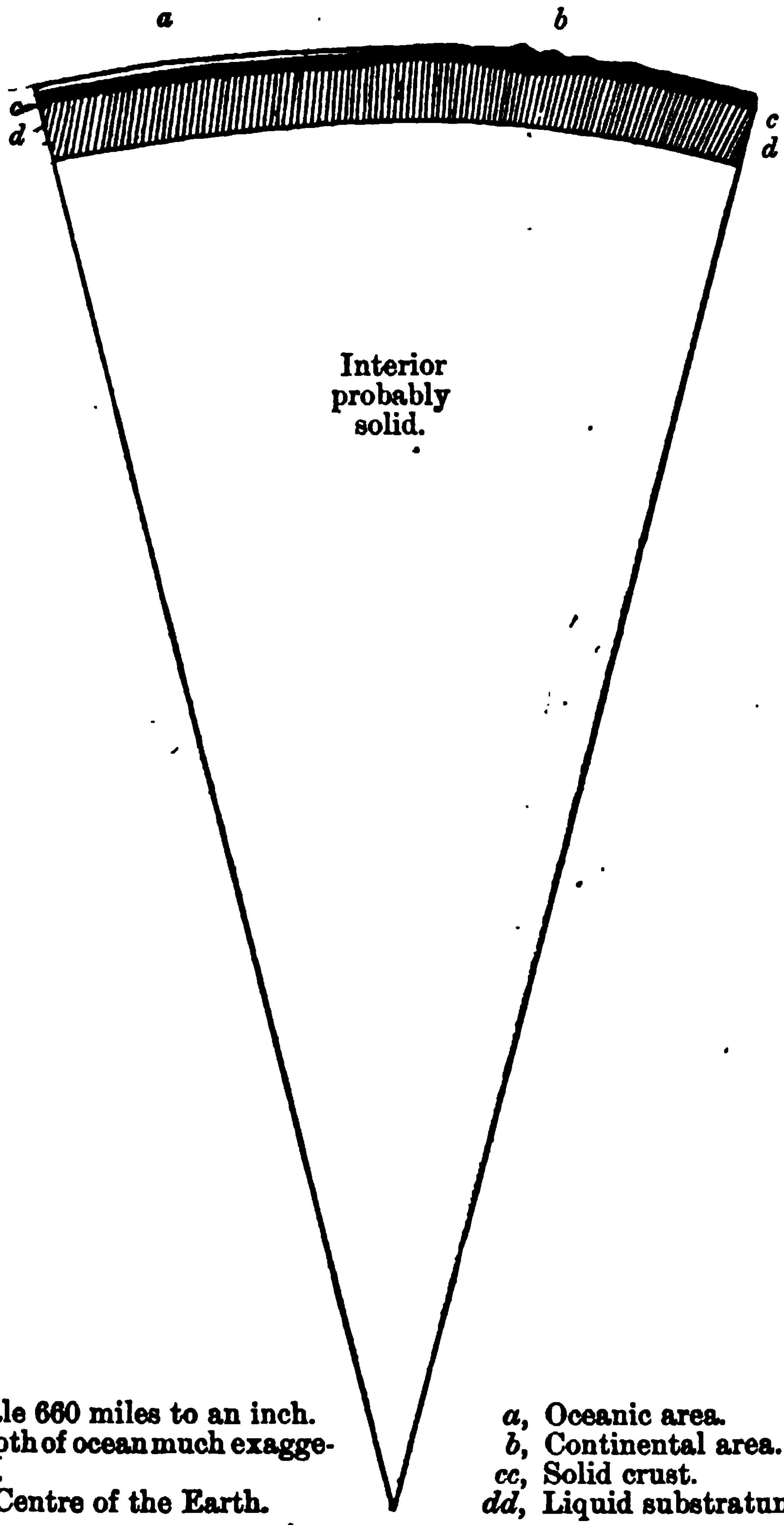
4. *Palæontology.*—Under this head will be given an outline of the laws which govern the distribution of life, both in space and time; but to deal fully with this part of the subject a separate volume would be required.

5. *Stratigraphy*, or *Historical Geology.*—Being a chronological account of the successive groups, or series of strata, which are found in the earth's crust. This will deal chiefly with the rocks of the British Islands, and will necessarily be only a condensed account, but prominence will be given to those facts which enable us to realize the relative positions of land and sea, and the general physical geography of each geological epoch.

PART I.

DYNAMICAL GEOLOGY.

SECTION I. Changes produced by the Influence of Internal or Subterranean Causes.



Scale 660 miles to an inch.
Depth of ocean much exaggerated.
x, Centre of the Earth.

a, Oceanic area.
b, Continental area.
cc, Solid crust.
dd, Liquid substratum.

Fig. 1. Diagram of a Segment of the Terrestrial Globe, to show its probable internal structure.

CHAPTER I.

THE GENERAL STRUCTURE OF THE EARTH.

THE Shape of the Earth, and its Consequences. —Everyone knows, or should know, that the earth has been both measured and weighed; and that the form of the globe is not that of a perfect sphere, but of an oblate spheroid. According to Mr. Clark, the equatorial diameter of the earth is 7925·604 miles in length, while the length of the polar diameter is only about 7899·114 miles; the difference between them is, therefore, a little less than 26·5 miles. That is to say, that the polar axis is almost exactly $26\frac{1}{2}$ miles shorter than an equatorial axis or line passing through the centre of the earth from one side of the equator to the other: or, again, as calculated along radii from the centre, an equatorial radius is about $13\frac{1}{4}$ miles, or 70,000 feet longer than a polar radius.

If, therefore, a true sphere were to be described within the earth, with a radius equal to that of the polar radius, the surface of this sphere would lie at the depth of 70,000 feet below the actual surface at the equator.

Now the deepest soundings in the ocean are less than 28,000 feet, and the highest mountain in the world, viz., Mount Everest in the Himalayas, is only 29,000 feet above the sea. Compared, therefore, with the bulging protuberance of the earth's mass at the equator, the irregularities of its surface, which we know as ocean-depths and mountain heights, are obviously small.

It is also seen that this equatorial bulge of 70,000 feet, though only about $\frac{1}{300}$ part of an equatorial radius, represents the bulk or weight of an enormous mass of matter, and its existence involves very important consequences.

The first of these consequences is the stability of the earth's axis. The earth is a body which revolves upon its own axis, that is, upon an imaginary line connecting its two poles, and this line is its shortest diameter. The actual circumference of the earth's equator is about 83 miles greater than that of the true sphere enclosed by it, consequently its linear velocity is more rapid than that of the inner sphere, because any point on it is carried round that greater space in the same period of time. Any cause, therefore, which tended to make the earth revolve upon any other axis than that of its shortest diameter, would have to overcome the resistance of the greater momental force residing in the equatorial protuberance; and ever since the earth first acquired its present form, it is very difficult to imagine any cause sufficient to have produced this result.

Hence we may conclude that the position of the earth's axis has remained unchanged throughout all geological time, or at any rate that it has never varied much from its present position, for there are some facts which are difficult to explain without imagining a certain amount of change in the position of the north pole; they cannot, however, be taken as proving such a change, and the poles have doubtless always been near their present positions.

The second conclusion deducible from the peculiar shape of the earth is the fact that it is almost exactly that of a spheroid of rotation; in other words, it is the form which the globe would have assumed had it been originally a pasty or fluid mass revolving with its present velocity.

The fact that the earth has this form raises a strong presumption that its condition was at one time sufficiently plastic to allow it to adjust its shape to the impulse of its motion; in short, that it was once in a fluid, semi-fluid, or pasty condition. Although this original plasticity is by no means a certainty, yet it is generally assumed as a probability, agreeing very well with some other known facts which are in favour of the idea, that the earth has been continually parting with heat, and that its own heat was once sufficient to keep its substance in a molten or semi-molten condition.

Internal Temperature of the Earth.—Without,

then, further considering the question of the possible temperature and condition of the earth in the earliest times, we will pass to a subject with which geology is more directly concerned; viz., the probable condition and temperature of its interior at the present time.

This is, of course, a very difficult matter upon which to obtain any evidence, but the following facts tend to show that it consists of a cool envelope surrounding a very hot interior, and that the latter possesses a high temperature of its own, quite independently of any heat derived from the sun or other external source.

1. *Volcanoes.*—The numerous volcanic orifices, which occur here and there all over the earth, and from which streams of lava or molten rock are so often poured forth, prove that some parts of the interior at any rate are so heated that solid rocks are rendered perfectly fluid. But the lavas derived from existing volcanoes form only a small portion of the bulk of igneous rocks in the crust of the earth, all of which have certainly come from some part of the interior.

2. *Temperature of Deep Mines.*—The influence of the summer's heat or winter's cold does not penetrate far into the interior of the earth, and it is estimated that at a depth of about fifty feet beneath any given place on the earth's surface a thermometer would mark the same temperature all the year round.

Below this limit of seasonal variation, sometimes called "the stratum of invariable temperature," and as far as any mines or borings have been carried into the earth, the temperature of the rocks always increases with the depth. This downward increment of temperature is not the same at all places, being sometimes rather more and sometimes rather less than the average, but there are many causes which would tend to produce variations in the rate at which the temperature increases downwards. One of the most important is that of the relative conductivity of the rocks, some kinds of rock being much better heat-conductors than other kinds, so that the rate of increase varies even in different parts of one boring.

Some of the earliest observations on the internal temperature of the earth were made by Mr. Henwood in

the mines of Cornwall and Devon. The result of his experiments in two hundred of these mines showed that the average temperature at different depths was as follows:—

Depth.	Temperature.
At 200 feet	About 57° Fahr.
„ 600 „	„ 62° Fahr.
„ 900 „	„ 68° Fahr.
„ 1,200 „	„ 78° Fahr.

The average increase below 300 being about 1° Fahr. for every 43 feet of descent. In the granite rocks, however, the temperatures were not quite so high.

In a coal-mine at Monkwearmouth, Durham, the temperature at a depth of 1,600 feet ranges between 78° and 80°, and observations showed that the increase in descending from the surface was about 1° Fahr. for every 60 feet.

In the Rose Bridge Colliery, near Wigan, however, a shaft has been carried down to a still greater depth, viz., 2,445 feet, and a careful series of observations were made by the manager, Mr. Bryham, during the process of sinking. The following are some of the results obtained:—

At a depth of	564 feet,	a temperature of	66° F.
„	1,674 „	„	78° F.
„	2,013 „	„	86° F.
„	2,445 „	„	94° F.

Assuming the surface temperature in this instance to be 50° F., these observations show an average increment of 1° for every 55 feet of depth.

While, then, there is some variation in the rate of this increase at different places, it is an undoubted fact that the temperature of the rocks does always increase after passing below the first 50 feet; and it appears that the average rate of this increase of temperature may be taken at about 1° F. for every 51 feet of depth.

3. *Temperature of the water in deep wells and borings.*—The temperature of the water at the bottom of deep borings is in agreement with this conclusion.

The water of the artesian well of Grenelle, near Paris,

which rises from a depth of 1,800 feet, has a constant temperature of nearly 82° F., which is about 31° hotter than the mean temperature of the ground beneath Paris. This, therefore, indicates a rate of increase of 1° for every 58 feet of depth.

Another well near Paris, at La Chapelle, where observations were taken at different depths, gave the following results :—

At	330	feet a	temperature of	59½° F.
„	660	„	„	62° F.
„	1,000	„	„	65½° F.
„	2,200	„	„	76° F.

These figures yield a slower rate of increase, viz., only 1° F. for every 82 feet.

At Sperenberg, near Berlin, a boring was made to a depth of 4,172 feet, nearly all through rock-salt, and the temperature observed at a depth of 4,042 feet, when corrected for pressure, gave a result of 1° F. for every 51½ feet.[1]

At Kentish Town (London) a well was sunk to a depth of 1,302 feet, and the temperature at the depth of 1,100 feet was found to be 69·9, giving a mean rate of increase from the surface of 1° F. for every 54 feet.

4. *Hot Springs.*—The Geysers and other hot springs which are found in volcanic districts, must be regarded as deriving their heat from the volcanic focus, and cannot be taken as affording independent evidence of the internal temperature of the earth. Warm springs, however, are not confined to such districts, but often occur in localities which are far removed from any recent or recently extinct volcanoes. In our own country the waters of Bath, with a temperature of 120° F., and those of Buxton, with a temperature of 82°, are instances.

There is little doubt that the waters of these springs travel upwards through cracks and fissures, which originate at great depths, and that they are hot in consequence of the depth from which they come.

[1] For a full account of the temperatures in this boring, and their teaching, see Fisher's "Physics of the Earth's Crust," 2nd ed., p. 7.

Internal Condition of the Earth.—The combined evidence of all the preceding considerations leads us to conclude that the interior of the earth is intensely hot.

Assuming the temperature of the invariable stratum beneath the British Isles to be 50° F.; and that below this the increase of temperature continues indefinitely into the interior at the same rate as that which obtains in our mines and wells, viz., about 1° for every 51 feet or $103\frac{1}{2}$° for every mile, we should shortly arrive at a very high temperature.

At a depth of 8,260 feet or less than two miles, the rocks would be as hot as boiling water, or 212° F.; at a depth of 27 miles they would be at a temperature of 2,794°, which is a heat sufficient to melt steel; and at 40 miles, a depth which is really only a little way towards the centre of the earth, we should find a temperature of 4,140°, which is a greater heat than any that we can produce at the surface.

It does not follow, however, as a necessary consequence that the materials which exist at these great depths would be melted at the same temperature that would fuse them at the surface, since the enormous pressure which they must sustain may keep them solid in spite of the heat.

It is well known that pressure retards or raises the melting-point of most solids, that is to say, an increase of pressure increases the temperature at which each is fusible. Very little, however, is known about the exact relations between pressure and the fusing-point of rocks, and it is possible that different substances are affected by pressure in a different ratio.

It has been supposed that the ratios of pressure and temperature within the earth are such that, below a certain depth, the pressure is only just sufficient to prevent the liquefaction of the rocks by the temperature proper to that depth, so that any local cause diminishing the pressure would allow of liquefaction.

Again, it is possible that the ratios of the increase of pressure and temperature are such that, at a certain depth, the pressure is insufficient to prevent liquefaction, and, consequently, that a certain thickness of the earth's mass is liquid; but that, at a still greater depth, the increased

pressure overcomes the influence of heat, and keeps the rocks solid, in spite of increased temperature.

Whether solid or fluid, we may safely assume that the interior of the earth has a very high temperature of its own, and if this is so, it must have been continually losing heat by conduction or convection from the interior to the surface, and this heat must have been dissipated into space. Consequently we are led back to the conclusion, which was foreshadowed on p. 10, that there was a time when the whole mass of the earth was in a molten or incandescent state, and that it has gradually cooled down to its present condition.

Assuming this to be the case, the condition of the earth's interior at the present time must depend upon the manner in which it has cooled, and Mr. Hopkins has shown that the earth's mass must now be in one of three different states; these are,[1]

1. A solid crust with a fluid interior.

2. A solid crust and a solid nucleus with a fluid interstratum.

3. Solid throughout, with or without fluid spaces or cavities.

Hopkins concluded that the balance of probability was in favour of the last (No. 3). He admitted,[2] however, that after the solidification of the nucleus there must have been a time when a solid external crust was formed resting on an imperfectly fluid mass beneath; but he thought that it must have grown to a thickness of not less than 800 or 1,000 miles at the present time, and that it had probably united itself to the internal nucleus.

He bases his opinion on the ground that the movements of precession and nutation could not be as they are, unless the crust possessed such a minimum thickness. Sir W. Thomson, however, has recently shown that these movements would still be experienced in the case of a thin crust covering a fluid substratum if the inner surface of the crust in contact with the fluid was not perfectly spherical. If this surface was only slightly irregular, the fluid and the

[1] Phil. Trans. Roy. Soc., 1839.
[2] Brit. Assoc. Rep., p. 48, note.

crust "would have sensibly the same precessional motion as if the whole constituted one rigid body."[1]

Sir W. Thomson has nevertheless expressed his concurrence with Mr. Hopkins' conclusion that the earth is either solid or possesses so thick a crust as to give it practical solidity. He considers that the tide-producing power of the sun and moon is so great that if the thickness of the crust was less than 2,000 miles, it would yield to the strain, and would be subject to periodic deformations similar to oceanic tides.[2] He says that, "the solid crust would yield so freely to the deforming influence of the sun and moon, that it would simply carry the waters of the ocean up and down with it, and there would be no sensible tidal rise and fall of water relatively to land." He concludes that the mass of the earth "is on the whole more rigid than a continuous solid globe of glass of the same diameter."

Prof. G. H. Darwin has also investigated the tidal deformation of viscous spheroids, and finds that Sir W. Thomson's results must be modified. In his first investigation (1879) he came to the conclusion that the effective rigidity of the earth was great, but not so great as that of glass or steel; and he adds that "no very considerable portion of the interior of the earth can even distantly approach the fluid condition."[3]

Still more recently Prof. Darwin has returned to the problem, which is one of extreme complexity, and obtains a result which he expresses as follows: "The present result shows that it is not possible to attain any estimate of the earth's rigidity in this way; but as the tides of the long period are distinctly sensible, we may accept the investigation in the "Natural Philosophy" as generally confirmatory of Thomson's view as to the effective rigidity of the earth's whole mass."[4]

Lastly, Mr. Fisher points out[5] that the most recent observations throw some doubt on the actual existence of the

[1] Brit. Assoc. Rep., 1876. Sectional Address, p. 5.
[2] Loc. cit., p. 7.
[3] Phil. Trans., 1879, Part I.
[4] "Nature," Jan. 20th, 1887.
[5] "Physics of the Earth's Crust," 2nd ed., p. 41, and Appendix, p. 34.

small fortnightly tide, on the theoretical existence of which the calculations of Thomson and Darwin are based. The whole matter is, in fact, fraught with so many difficulties and uncertainties, that geologists need not consider the results obtained as in any degree approaching to mathematical demonstrations.

Mr. Fisher, moreover, meets the whole case of the astronomers by the following hypothesis: he assumes that there is a liquid substratum, suggesting that it consists *not of melted rock only*, but of an intimate mixture of *fused rock and gas*, the gas being, in fact, dissolved in the liquid magma. This gas may be pure hydrogen, or it may be some compound of hydrogen, such as water, maintained in the state of a gas by the great heat of the interior.

This supposition of a liquid substratum containing dissolved gases is supported by much geological evidence. Steam and gases of various kinds are given off in large quantities during volcanic eruptions. The observations of Siemens on Vesuvius in 1878, and of Fouqué on the eruptions of Santorin (1810), have shown that hydrogen is one of the most abundant gases in such eruptions. Siemens concluded that vast quantities of hydrogen gas, or of combustible compounds of hydrogen, must exist in the earth's interior, and that portions escape through the volcanic outlets. It is also supposed to be the rise of these superheated gases which keeps the lava inside a volcano hot and liquid.

Mr. Fisher therefore assumes the existence of a liquid substratum which is saturated with gases, and is therefore expansible; and he endeavours to ascertain how such a magma would behave in respect to the formation of tides. The materials for a proper examination of this problem do not yet exist—one of the desiderata being experiments on the capacity of molten rock (such as slag) for dissolving gases; but if the case is similar to the solubility of certain gases in water, and with certain other conditions which are not improbable, Mr. Fisher shows that there would not necessarily be any tide in the substratum which would affect the level of its surface, or cause any rise or fall of the overlying crust.

Mr. Fisher's argument if sound is of great importance to

geologists, who have always felt great difficulty in accounting for various geological phenomena on the supposition of the earth being a solid and rigid globe; they have always been inclined to believe in the liquidity of some portion of the earth's interior, for it is only on this assumption that they are able to explain the occurrence of volcanoes, earthquakes, and other earth movements, or the fact that volcanic products are similar all over the world, as if derived from a common source.[1]

Assuming the existence of a continuous liquid substratum, Mr. Fisher adduces physical arguments for supposing that the thickness of the overlying crust is not everywhere the same; that its average thickness at the sea-level is about 25 miles; that it is thicker than this under mountain chains, and thinner under the oceans. To this question we shall have occasion to recur in the sequel.

In this chapter we have briefly discussed the views which have been held by the best modern authorities respecting the structure and condition of the earth's interior. We have seen that the most probable conclusions are—

1. That the interior is very hot.
2. That a portion of it is liquid, and forms a continuous layer between the solid crust and the central mass, whether that be solid or plastic (see fig. 1, p. 8).
3. That the solid crust is comparatively thin.
4. That the liquid layer is saturated with dissolved gases.

It is obvious that under such conditions the earth's crust is not likely to be perfectly rigid and unyielding, and that if any causes exist which tend to alter the equilibrium of the crust, movements of various kinds are likely to be produced. The crust, in fact, would give evidence of decided instability.

As a matter of fact we know that such movements do take place all over the globe. Volcanoes pour forth vast quantities of molten matter; earthquakes shake large

[1] Another mathematician, Professor Harkness, has also admitted the force of the arguments against the solidity of the earth, and the possibility of a thin crust resting in hydrostatic equilibrium on a denser substratum. ("On the Solar Parallax," Washington, 1891.)

tracts of ground, and often produce permanent changes in the relative level of land and sea; and lastly, there is evidence to prove that slow and gradual movements of the crust have been in progress over still larger areas, the land being elevated in one place and depressed in another. Finally it will appear that every part of the land has been below the sea at some period of past time, and is now dry land only because it has been elevated by the movements above mentioned.

It is important that the geological student should thus early realize the fact of the instability of the earth's crust, proofs of which will be given in the next four chapters, for he will find evidence of the strains, pressures, and movements to which the rocks have been subjected in every branch of geological study.

CHAPTER II.

VOLCANOES.

GENERAL Form and Structure.—A volcano may be defined as a conical pile of materials which have been ejected from the orifice of a pipe or fissure communicating with a highly heated portion of the earth's crust below. The materials composing the cone are chiefly fragments of rock which have been violently discharged into the air, and have fallen on all sides round the central orifice or *crater* as it is called. Every eruption adds to the pile and increases the height and magnitude of the volcano; great blocks as well as small stones, cinders, and ashes are thrown up and fall on all sides of the mountain. Floods of lava now and then boil up, and either break through the sides of the cone or run over the lip of the crater, and flow down into the adjacent country in the form of lava streams. Successive eruptions frequently take place from the same vent, but minor cones are often formed on the flanks of the larger one, and lesser eruptions proceed from them.

Volcanoes are sometimes isolated mountains like Vesuvius and Etna, but are more frequently arranged as a row of cones and peaks along straight or slightly curved lines, as if they had been thrown up at intervals along the course of great linear fissures in the earth's crust; such are the chains of the Andes, the Aleutian Islands, and the Malay Archipelago. These lines of volcanic vents sometimes seem to radiate from a special volcanic centre.

If we could make a vertical cut or section through a volcanic hill, so as to lay open its internal structure from the summit to the ground it rests upon, we should find this structure to be similar to that suggested in the diagram,

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found, which consists almost entirely of lava-flows. Such a volcano does not form a conical mountain, but a broad low dome-shaped one, its slopes being seldom steeper than 10°, whereas those of ordinary volcanoes often slope at angles of 28° and 30°. Volcanoes of this type do not possess a true crater, but only a central pit or *caldera*, and though the lava sometimes issues from this, it more often breaks forth from the flanks of the dome. The lavas ejected from these openings sometimes accumulate till they form a huge mound-shaped mass many thousand feet high, and covering an immense area of ground. Fig. 3 represents the outline of such a mound, in which the solidified lava-flows would show in section as so many overlapping lenticular cakes intersected by dykes of lava leading up to the orifices from which the lavas have issued.

Phenomena of an Eruption.—The two types of volcanic vents above described correspond with certain

Fig. 3. Outline of a Lava-Mountain (Mount Loa, Hawaii).

special characteristics of the eruptions by which they have been formed: the one kind may be termed explosive eruptions, and the other kind non-explosive eruptions.

A. *Explosive Eruptions.*—These usually exhibit the following succession of phenomena. The first intimations of the disturbance are generally loud rumbling sounds which seem to proceed from the interior of the mountain. Shocks of earthquake frequently succeed these noises; the water in wells and springs sink down in consequence of the opening of rents and fissures below; and finally, owing to the transmission of submarine shocks, the sea often ebbs and flows in an unnatural manner.

After these general disturbances, which are sufficiently alarming, the phenomena begin to be concentrated in the crater, and usually occur in the following order:—

1. An explosive discharge of steam, falling in rain.
2. A discharge of dust, ashes, and stones.
3. The ejection of larger blocks with heavier explosions:

at the same time the red glow of the lava rising in the funnel lights up the vapour-clouds above, and produces the appearance of flames.

4. The lava rises and finds egress either from the crater or from lateral openings.

5. When the flow of lava ceases there is frequently a discharge of black sand or comminuted pumice. In some cases the eruption does not proceed farther than stage No. 2; but in violent eruptions there is a continued repetition of heavy explosions and outflows of lava.

Some volcanoes are in a state of constant activity, small explosions taking place incessantly at short intervals, while occasionally more violent outbursts occur, and streams of incandescent lava are poured forth. In other cases periods of quiescence alternate with periods of activity, and when eruptions do occur they are generally of a violent description.

From the records which we possess relating to the Italian volcanoes, it would appear that the same volcanic centre may exhibit both phases at different times; the eruptions being sometimes incessant and of moderate intensity for a long time, then ceasing, and a state of quiescence ensuing, which is broken by a more violent outburst. It has been noticed, indeed, that there is a distinct relation between the violence of an eruption and the length of the intervening periods of repose, so that the following rules may be laid down:[1]—

1. Feeble and short eruptions usually recur at brief intervals.

2. Violent or long-continued eruptions are generally followed by long periods of repose.

3. A long period of repose is often succeeded by an eruption which is either of long duration or of great violence.

Truncation of the Cone.—Sometimes a violent outburst of the volcanic force will blow the upper part of the cone completely away, and thus destroy what it has taken ages to build up. The volcano then presents the appearance of a truncated cone with a huge gaping hollow in the centre. Subsequent eruptions, however, repair the damage by

[1] See "Volcanoes," by J. W. Judd, p. 33.

forming a new cone in the interior of the great hollow; so that the mountain eventually consists of a lofty circular ridge surrounding a central depression, from the floor of which rises the new and active volcanic cone (as indicated in fig. 4). This formation of a new cone within an older truncated one is of frequent occurrence in the history of volcanoes. Vesuvius is known to have presented this appearance at several periods, and is even now partially surrounded by the old crater-ring called Monte Somma (see fig. 5).

Barren Island, in the Bay of Bengal, is an excellent instance of this form of volcano, as represented in fig. 4. Here the whole central part of the mountain has been blown out by one tremendous explosion, the outline which

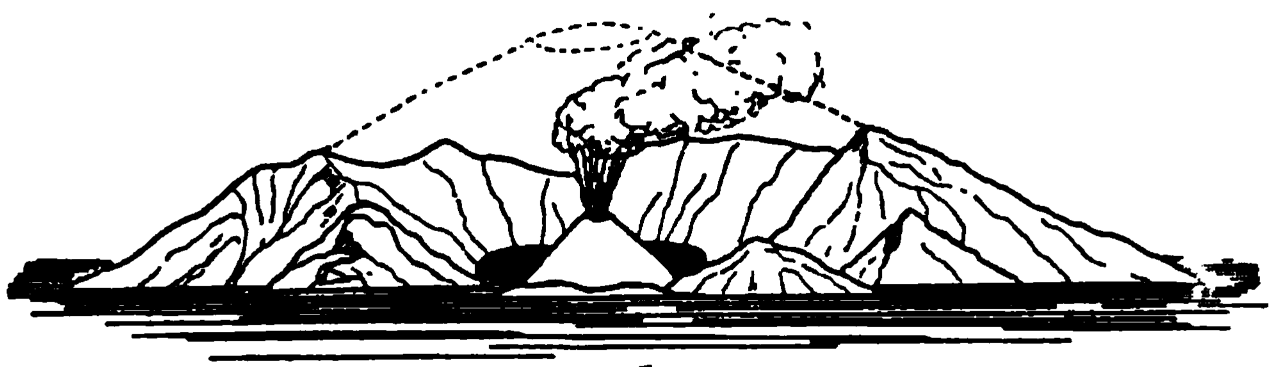

Fig. 4. Outline of Barren Island, after Scrope.

the cone must have originally possessed being indicated by the dotted line.

The Peak of Teneriffe is another example in which the central cone rises far above the encircling ring of the older truncated mountain.

B. *Non-Explosive Eruptions.*—These are not generally preceded by any violent disturbances, though occasionally earthquakes of some severity occur. As a rule also there are no explosive discharges of steam, dust, or stones, but sometimes small discharges of this kind are thrown up from points along the fissures which are rent through the mountain. The rise of the lava in the central pipe of the volcano is generally slow, sometimes rising and falling again, till it either flows over the lip of the caldera or bursts a passage at some point lower down. When the latter is the case, it is forced up in jets or fountains of red-hot liquid, from which rivers of lava course down the slopes; these

lavas being generally so fluid that they form streams 50 or 60 miles in length. Our knowledge of these kind of eruptions is chiefly derived from the volcanoes of Hawaii in the Pacific Ocean.

Products of an Eruption.—These may be classified and described in the following order :—1. Steam and gases; 2. Stones and ashes; 3. Lava.

1. *Steam and Gases.*—During an explosive eruption steam is always discharged in great quantities, bursting forth with a roaring sound from the crater, and sometimes also from vents and fissures on the sides of the mountain. The perpendicular uprush of steam from the crater spreads out above into a great horizontal cloud of vapour, the outline of the column and cloud together seen from a distance bearing much resemblance to that of a pine-tree very common in Italy, and known as the *stone-pine* (see fig. 5).

Around this column vivid flashes of lightning are constantly playing, the electricity being produced by the friction of the uprushing current of steam as it escapes through the shaft or funnel of the volcano, and partly also by the collision of the fragments which are carried upward with it. The air at length becomes loaded with vapour which falls in heavy rain, thunder-storms are frequent, and great floods are thereby occasioned. The rain-water courses down the slopes and sweeps along the loose volcanic dust and ash, forming muddy torrents, which often work more damage and destruction than the streams of lava.

Besides steam the following gases are emitted from volcanoes :—carbonic acid, hydrochloric acid, sulphurous acid, sulphuretted hydrogen, and boracic acid; together with hydrogen, nitrogen, and ammonia. By the action of these gases on the materials of the cooling lavas and surrounding rocks, a number of secondary products are formed, consisting of the chlorides and sulphates of various earths, sulphur and sulphides of certain metals. When sulphurous acid and sulphuretted hydrogen come into contact with each other, a chemical action takes place, which results in the formation of water and sulphuric acid, and the liberation of a certain amount of pure sulphur. This sulphur rémains in the fissures and cavities where the com-

bination takes place, the water is evaporated, and the sulphuric acid forms sulphates by combining with lime, iron, soda, and other substances.

2. *Fragmental Products.*—The solid materials ejected during an eruption are of various sizes and kinds. Some are fragments of the rocks which underlie the volcano, such as limestone or shale. These have been broken off, and blown out by the force of the explosions; but the greater number of the ejected fragments are pieces of molten rock or lava. The viscid scum which forms on the surface of the rising lava prevents the free escape of the steam which is constantly ascending through the mass; the steam, therefore, collects into great bubbles, which eventually burst, and the pressure being then relieved, a general escape of steam takes place with explosive violence, and fragments of the semi-liquid material are hurled high into the air. Among these there are sometimes blocks of large size, which, rotating as they rise, come to assume a spheroidal form; these are called *volcanic bombs.* Smaller cindery fragments are termed cinders or *scoriæ.* Some of these blocks and cinders fall outside the crater; but many fall inside, and are ejected again and again, hurtling against one another in the air, till they are reduced to fragments of still smaller dimensions (*lapilli*), while great quantities of mere dust and ash are produced at the same time.

The accumulations of coarser *débris* include fragments of all sizes, and form the rock known as *volcanic agglomerate.* In some cases blocks derived from the strata underlying the volcano are very numerous, but according to Mr. Johnston-Lavis they are only ejected during very violent explosive eruptions, when the pit of the crater extends down into the foundation rocks. "Another group of ejected blocks consists of coarsely crystalline varieties of the lava that usually issues from the volcano, and these are no doubt portions of the magma that have cooled as dykes during a period of quiescence, and have subsequently been torn off by explosions."[1] The stones and cinders which fall on the inward slopes of the crater roll down again into its mouth;

[1] Johnston-Lavis on "Ejectamenta of Volcanoes," Proc. Geol. Assoc., vol. ix. p. 432.

ct., 1822.

and, at the close of an eruption, the crater and funnel are sometimes choked up with an agglomerate of these materials.

The rain, which is constantly falling during a long-continued eruption, mingles with the fine volcanic dust, and produces a peculiar pasty kind of mud, which sets into a firm, but light and porous stone, and is known by the name of *tuff* or *tufa*. It often encloses and is partly made up of lapilli, scoriæ, and broken crystals, and is then generally known as *volcanic ash*, or by the French *cinerite*, and by the Italians *peperino*.

The more liquid and glassy lavas, when distended by the formation of steam, give rise to a kind of lava-foam or froth, which is often ejected in large quantities, and when cooled forms the porous grey or whitish substance known as pumice. "What really occurs," says Mr. Johnston-Lavis, "is an intermolecular separation of the dissolved water, its conversion into steam, and its union in bubbles of all sizes, which, owing to the rapid cooling, are prevented from escaping except on the surface, as is shown by the more compact crust of pumice-masses." (*Op. cit.* p. 424.)

A strong wind blowing at the time sometimes causes a greater accumulation on one side of the mountain than on the other. The finer dust and powder is often ejected to such a height as to be carried by the upper currents of the atmosphere for hundreds and even thousands of miles before being dropped. In 1835 the dust and ashes from Coseguina, in Nicaragua, fell in the streets of Kingston, Jamaica, 700 miles distant, while the ground for 30 miles south of the volcano was covered with a layer ten feet thick, destroying the woods and dwellings, and enveloping thousands of animals which were unable to escape from the sudden fall of the dense dust-cloud.

During the eruptions of 1874-75 in Iceland, large tracts of the adjoining country were covered with a thick blanket of ashes, and fine dust fell in considerable quantities over certain parts of Norway and Sweden.

The great eruption of Krakatau, between Java and Sumatra, in 1883, is memorable not only for its terrific violence and destructive force, but for the prodigious quantities of dust and pumice which were ejected; the dust

was carried into the higher regions of the air and travelled to immense distances, producing atmospheric phenomena over the greater part of the globe; the amount of pumice was so great in the Straits of Sunda that vessels had some difficulty in forcing their way through it, and thence, floating on the water, it was driven by the winds and currents over the greater part of the Indian Ocean.

3. *Lavas.*—Lava-streams vary considerably in their degree of fluidity, and, consequently, in the rapidity with which they flow. In some cases the lava is so liquid that it pours rapidly down the slopes of the cone like a river, and flows far out from the base of the volcano; but more usually it only preserves its fluidity for a short distance from the point of exit, a rough slaggy crust quickly forming over the surface of the *coulée*, though the lava beneath is still viscid, and the whole mass continues to move forward.

A viscous lava which is saturated with gas always has a rough, cindery, and vesicular crust, so much so that its surface is sometimes broken up by the rapid movement into large cindery blocks with sharp ragged projections. The lower end of such a stream has been described as a slowly-moving mass of loose porous blocks, gradually rolling and tumbling over each other, with a loud rattling noise, as they are forced along by the pressure of the viscid mass of cooling lava below. A more liquid lava, containing less gaseous matter, generally has a crust that is wrinkled and twisted into ropy forms, such as are often seen on the surfaces of artificial slags.

The liquidity of a lava seems to depend partly on chemical composition, partly on the amount of gaseous matter which it includes, and partly on the temperature it possesses at the time of ejection. As regards chemical composition, lavas differ principally in the amount of silica they contain, which varies from about 45 to 80 per cent. Those with a high proportion of silica are known as *acid* lavas, and when cooled they form Rhyolite and Obsidian; those with only 45 to 55 per cent. of silica are termed *basic* lavas, and when cooled they form Basalt and its varieties. Between these two extremes there are various intermediate kinds, such as form Trachyte and Andesite.

The amount of gas and steam given off during an eruption, and from the surface of lava-flows, varies considerably. Many lavas, such as those of Vesuvius, are so saturated with water-gas that the flowing lava is often quite concealed from view in a dense cloud of steam, which is blown off from hundreds of small vents and spiracles all over the surface of the stream. Other lavas, both acid and basic, well up more quietly, and contain but little steam or gas, or else they part with it in a less explosive manner.

Lastly, as to the temperature of lavas at the moment of issue, there is little doubt that this differs in different cases and places, but its actual amount in any case has not yet been ascertained, owing to the difficulties of observation. Copper wire has been melted in lava which indicates a heat of about 2,200° F. The complete fusion of the basic slags which are formed in an iron furnace occurs at about 2,700° F., and we may therefore assume that the temperature of liquid basic lava is at least as much, while for the fusion of an acid lava a greater heat must be necessary.

Lavas, however, are not always in a state of complete fusion; observations have shown that it often consists of a pasty or semi-fluid mass, in which are floating a number of crystals and crystalline particles of several different minerals. These crystals bear evidence to having been formed under great pressure, and in the presence of superheated steam or gas, and have evidently originated while the lava was in the pipe of the volcano. As the lava cools the pasty mass also crystallizes, and forms a finely crystalline stone enveloping the larger separate and previously-formed crystals.

As all rock is a bad conductor of heat, so, when the crust has once formed, the internal portion of the lava-stream always remains hot for a long period of time. The process of solidification is, therefore, a very gradual one; and a great thickness of lava takes a proportionately long time to cool, and solidify into stone. Natural sections of lava-streams in cliffs or ravines show that the upper and lower layers of the cooled mass are always more or less vesicular and scoriaceous, while the central portion is a hard, compact, and frequently a crystalline stone.

The gradual cooling of the lava causes it to contract, and

leads to the production of cracks, which traverse the whole mass from top to bottom. These are sometimes so regular as to split the mass up into a series of hexagonal prisms or rude columns, similar to those assumed by starch and other substances in passing slowly from a fluid to a solid state. This structure will be more particularly described in Part II.

Slow-moving lavas are frequently congealed before they arrive at the base of the cone, but the more liquid lavas often flow to a distance of many miles from the point of eruption. Some lava-currents from Vesuvius are said to have flowed a mile and a half in fourteen minutes, and others a distance of nearly two miles in the space of three hours. The stream which issued from one of the lateral cones of Etna, and destroyed Catania in 1669, was 14 miles in length, with a width of 5 miles in some places. The floods of lava, however, which issued from Skaptar Yokul in Iceland, in the year 1783, are the most extraordinary on record. One of these lava-streams was 50 miles long, with a width of from 12 to 15 miles; another was 40 miles long, with an occasional width of 7 miles; both had an average depth of 100 feet, increasing here and there in narrow ravines to a depth of 500 or 600 feet.

Formation of Lava-filled Fissures.—The position which volcanoes apparently hold in relation to lines of fissure in the earth's crust has already been mentioned; and the dykes which traverse the cone itself have been spoken of as cracks injected with lava. The actual formation of such fissures has, indeed, been observed; and Sir Charles Lyell gives the following account of one which opened in the plain of St. Lio, near Etna:[1]—"A fissure 6 feet broad, and of unknown depth, opened with a loud crash, and ran in a tortuous course to within a mile of the summit of Etna. Its direction was from north to south, and its length 12 miles. It emitted a most vivid light, indicating that the fissure was filled with incandescent lava, probably to the height of an orifice not far from Monte Rossi, which at that time opened and poured out a lava-current. When the melted matter in such a rent has

[1] "Principles of Geology," tenth edition, vol. ii. p. 21.

cooled, it must become a solid wall or dyke, intersecting the older rocks of which the mountain is composed." There is every reason to believe that the fissures over which volcanoes stand are similarly filled with molten rock, and are, in fact, the feeders or reservoirs of the volcanic vents. On the cessation of volcanic activity in the district these lava-filled fissures must remain as enormous dykes, extending for long distances, and cutting through all the rocks of which the country is composed. Such dykes are sometimes found extending for distances of 50 or 100 miles across the country; and in Iceland, during the eruption of Skaptar Yokul, in 1783, "lava was emitted consecutively at several points on a linear range of 200 miles," a lava-filled fissure doubtless extending throughout the whole of this distance, and now remaining as a solid dyke.[1]

Such dykes, as Lyell observes, may be called the roots of the volcano, reaching downwards to the regions of subterranean fire, while the external cone, with its lava-streams and loose ashes, may be likened to the branches and light foliage; and, to complete the simile, we may consider the central pipe or chimney to be the stock or trunk of the volcanic tree through which the lava-sap rises from the deep-seated roots to feed the sub-aerial branches.

Exciting Causes of Volcanic Action.—This is rather an abstruse subject upon which to enter near the beginning of a treatise on Geology, but we shall endeavour to put the results of recent researches as simply and briefly as possible. With respect to the immediate cause of eruption—that is to say, the force which causes the explosions, and raises the lava in the volcano—there is a general agreement of opinion, and this has been so well expressed by Professor Judd that his words are here quoted:[2] "That the molten materials which issue from volcanic vents have absorbed enormous quantities of steam and other gases we have the most indisputable evidence. The volume of such gases given off during volcanic outbursts, and while the lava streams are flowing and consolidating, is enormous. . . . It is to the violent escape of these gases from the

[1] Scrope, "Volcanoes," p. 52.
[2] "Volcanoes," Internat. Scientific Series, second edition, p. 357.

molten rock-masses, as the pressure upon them is relieved, that nearly all the active phenomena of volcanoes must be referred; and it was the recognition of this fact by Spalkanzani, while he was watching the phenomena displayed in the crater of Stromboli, which laid the foundations of the science of Vulcanology."

But other questions here present themselves: at what point and in what manner did the gaseous material gain access to the molten rock, and how did it come to be occluded or confined within it? It has been supposed that the water might be supplied by a downward percolation from the oceans and other surface waters, and that even at great depths a capillary conduction of water would still take place toward the earth's interior; but although there is much evidence to show that surface waters do penetrate to great depths, and that they do actually gain access to the ducts of volcanoes when once these have been established, yet it is impossible to conceive that water could penetrate the solid crust of the earth to a depth of 25 or 30 miles, so as to become the initial cause of volcanic action. Not the minutest crack or interstitial space can exist at a depth where the rocks must be in a plastic condition under the influence of enormous heat and pressure. If we could imagine the existence of cavities at such depths, capillary action might be set up; but this seems to be impossible.[1]

It is much more likely that the water-substance is dissolved or occluded in a liquid substratum of fused rock, its presence there being accounted for in the same way as the presence of other oxygen compounds, that is to say, its materials existed originally in the form of oxygen and hydrogen gases, and it is only when and where conditions allow of their combination that water-substance is formed. If the conditions of the liquid substratum have allowed of this combination, the water is still a gas dissolved in the liquid, for it is a well-known fact that all liquids can absorb large quantities of gaseous matter, and that the quantity so absorbed (though not the volume) is increased by pres-

[1] For a refutation of the theory of capillary penetration and volcanic action suggested by M. Daubrée, see Fisher's "Physics of the Earth's Crust," second edition, p. 143.

sure. On the relief of pressure, the expansion of the water-gas would lessen the specific gravity of the liquid and enable it to rise, while if it reached the surface explosive ebullition might take place.

That the escape of such occluded gas can produce volcanic action we have an interesting demonstration in the phenomena exhibited by cooling sulphur during the process of its extraction from soda-residues. The molten sulphur is exposed to a temperature of 262° F. and a pressure of two or three atmospheres, in the presence of steam. Under these circumstances it is found that the sulphur absorbs a considerable amount of steam; and when the mass is allowed to cool and solidify, this is expelled again with great violence. The hardened surface crust is agitated and fissured, miniature cones and lava-streams being formed upon it which have a striking resemblance to the grander phenomena of the same kind which occur on the surface of the earth.

In the presence of confined steam or gas we have, therefore, a competent cause of volcanic action, if a way was once made for its escape through the crust of the earth. This is probably accomplished by the strains to which the lower part of the earth's crust is subjected, aided by movements in the form of convection currents occurring in the subjacent liquid stratum, and resulting in the production of fissures along certain lines of weakness in the crust; but further consideration of the subject must be deferred till the student has acquired more knowledge of structural geology; and, after all, we can but guess at the exact *modus operandi* of the forces concerned in producing a volcano.

CHAPTER III.

VOLCANOES (*continued*).

EXAMPLES of Volcanic Action.—*Vesuvius and the Phlegræan Fields.*[1]—The volcanic region of Naples consists of a linear group of cones, ranging N.E. and S.W., and terminated at its extremities by the two principal mountains, Ischia and Vesuvius; the latter seems to be connected by the intervention of minor vents with the group of Albano and of Rome—the seven hills of the Eternal City being for the most part volcanic mounds.[2]

The celebrated mountain of Vesuvius consists of a central peak, half encircled by the remnant of a more ancient cone, which now forms the ridge known as Monte Somma, the depression between them being called the Atrio del Cavallo. Viewed from the south-west its general outline is exceedingly regular, though its summit is now broken and truncated. Mr. Scrope observes that this regularity is owing to the great fluidity of its basaltic lavas, which, issuing from the central vent, have taken their course in spreading sheets down the outer slope of the mountain, while the scoriæ and fragmentary substances projected at the same time into the air were spread pretty evenly over them.

"The result of successive eruptions of this kind has been the formation of a regularly conical mountain, with a gradually diminishing slope on all sides, from the central heights to the plain around, exhibiting in the ravines that

[1] Some of the following passages are quoted from Mantell's "Wonders of Geology," seventh edition, p. 843 *et seq.*, and were chiefly compiled from the writings of Mr. Poulett Scrope.

[2] See Murchison, "Quart. Journ. Geol. Soc.," vol. vi. p. 281.

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Roman army. It does not appear that the volcanic character of Vesuvius was then recognized; the Roman writers describe its slopes as bearing fertile fields and rich vineyards, while the hollow at the top was a waste overgrown with wild vines. The explosive eruption of A.D. 79 blew out the southern side of this great crater, and the present cone, which rises to about 1,000 feet above the Atrio del Cavallo, has been gradually built up by the successive eruptions of eighteen centuries, though in the course of that period it has several times been partially destroyed and again reconstructed.

"The eruptions of Vesuvius seem very rarely to have taken place from any other than the central vent; a few small cones immediately above Torre del Greco, thrown up in 1794, and the cone on which the Camaldoli della Torre is built, are the only indications of explosions having burst from the sides of the mountain. The vast number of vertical basaltic dykes which intersect the horizontal beds observable in the broken cliffs of the old crater (Atrio del Cavallo), bear witness, however, that the lava was not so frequently elevated to the summit of the mountain without occasioning numberless cracks and rents in its internal structure."

When Italy was first colonized by the Greeks, Vesuvius was in a quiescent or dormant state, while the neighbouring isles of Ischia and Procida were the theatres of constant earthquakes and explosions: but since Vesuvius has resumed its activity, Ischia has been almost entirely dormant. Ischia has numerous cones; the central one, Epomeo, is 2,600 feet high, and has traces of two large craters on its summit; but eruptions have burst out at various points, and a lava-stream that issued from its base still exhibits an arid and cindery surface.

The Lipari Isles between Naples and Sicily, lying, as it were, midway between Vesuvius and Etna, present a character very analogous to the district above described.

The crater of one of the islands, Stromboli, has been in constant activity from the earliest historical period. It always contains melted lava in constant motion, and at uncertain intervals the molten mass suddenly rises, and large bubbles appear, which, upon reaching to the brim of

the crater, explode with a sound resembling thunder; masses of lava, with dust and smoke, are thrown into the air, and the incandescent fluid then sinks down to its former level.

The cliffs of St. Calogero, which are about 200 feet high, and extend four or five miles along the coast, consist of horizontal beds of volcanic tuff, traversed in every direction by dykes and veins of lava.

Etna.—This volcanic cone rises majestically to the height of more than two miles (10,872 feet), the circumference of its base exceeding 180 miles. Compared with this prodigious mass of igneous products, Vesuvius sinks into insignificance, for while the lava-streams of the latter do not exceed seven miles, those of Etna are often from 15 to 30 miles in length, and from 50 to 100 feet in thickness. The surface of Etna presents three distinct regions; around the lower slopes the country is richly cultivated, and abounds in vineyards and pastures, towns and villages; the middle or temperate zone above is covered with forests of oak and chestnut; but upwards the trees grow sparse and small, and the last 5,000 feet form a bare and sterile region, while the summit is capped with eternal snow.

As a volcano Etna possesses two remarkable features—
1. The number of minor cones which have been thrown up on its flanks, no fewer than 200 such lateral vents being known. In 1809 twelve new craters opened about halfway down the mountain, and threw out copious streams of lava; again, in 1811, other vents appeared on the eastern side.

2. But by far the most interesting feature of Etna is an immense depression or excavation on the eastern side of the mountain, called the *Val del Bove.* This vast hollow is 5 miles across, and its sides are precipices from 2,000 to 3,000 feet in height.

There is good reason to believe that the Val del Bove contains the site of a second focus of eruption, and that the materials which once occupied it were blown away by explosions similar to those which removed the central portion of Somma, before the modern cone of Vesuvius was built up. If so, the new cone, which forms the present summit of Etna, did not rise within the old crater, but

quite outside its limits. Other cases, in which the volcanic focus has shifted its position, are not rare, and examples are found in Vulcano and Vulcanello, two of the Lipari islands.[1]

The precipitous sides of the Val del Bove are everywhere seamed by vertical dykes, which not only intersect the concentric sheets of lava and tuff, but, standing out in bold relief, like prodigious buttresses, impart a most extraordinary character to the scene. These buttresses are from two to twenty feet in thickness, and their superior hardness has enabled them to resist the action of rain and frost better than the less coherent tuffs around them.

Professor Blake remarks [2] that if the directions of these dykes are prolonged, the points of their intersection would lie within the area of the Val del Bove. This, and the fact that numerous eruptions have issued from the floor of the valley, confirm the view that it is a kind of crater.

Lyell describes the plain of Trifolietto, as the floor of the valley is called, "as more uneven than the surface of the most tempestuous sea"; but Professor Blake says "the great lava stream of 1852, erupted since he saw the spot, must have entirely changed the aspect. The fluid mass must have been kept up by a ridge of rock extending from Cavanno on this side to Monte Fenoccio on the other, and have settled itself into a smooth and lake-like surface, over which the winds have spread a coating of the finest dust."

At the further end of this plain are two tuff cones from which small lava-flows have issued, and below them are the two boccas, or low lava-mounds, whence more liquid and voluminous flows like that of 1852 have issued. "It is very instructive to have the two forms of eruptive centres thus side by side, and to compare the effects. The results produced by the cinder cones are confined to their immediate neighbourhoods, but by comparison with the huge lava-sheet which has overwhelmed all the country as far as Zaffarana, the Bocca is quite insignificant. This is important to remember when we find a difficulty in identifying the centre of ancient lava-flows."

[1] See "Volcanoes," by J. W. Judd, for illustrations of this and other features of volcanoes.

[2] Proc. Geol. Assoc., vol. xi. (1889), p. 169.

Hawaii.—The Sandwich Islands in the North Pacific are the best known examples of volcanoes formed by the welling up of lava without explosive action. They are all volcanic, and all exhibit similar features, though only one of them (Hawaii) now has active vents. Recent soundings have disclosed the fact that these islands are the summits of a gigantic submarine mountain chain, the loftier peaks

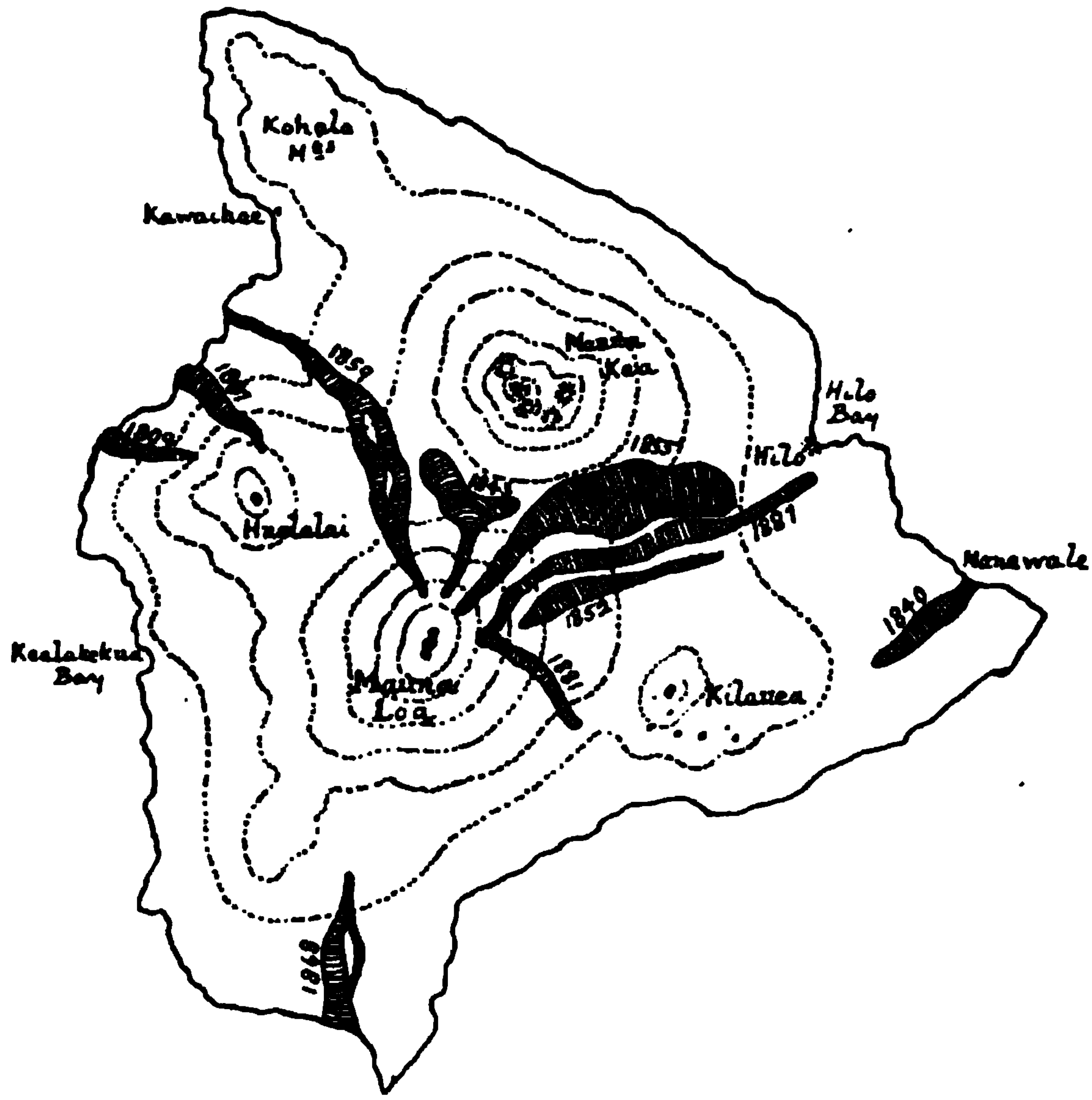

Fig. 7. Map of the island of Hawaii, showing some of the recent lava streams. The dotted lines are contours of 2,000 feet interval.

of which are not far off 30,000 feet above their sub-oceanic bases. The depth of the water within thirty or forty miles of Hawaii varies from 14,000 to 16,000 feet, and the Hawaian volcanoes rise to nearly 14,000 feet above the sea.

Hawaii comprises four volcanic centres, one of which is

apparently extinct (Mauna Kea); but three (Mauna Loa, Hualalai, and Kilauea) are still active. As already stated (p. 24), the most notable characteristics of their eruptions are (1) the comparatively quiet uprise of the lava and the consequent absence of fragmentary ejecta; (2) the great liquidity of the lavas. To these causes the low, broad outline of the mountains is due (see fig. 3). The positions of these centres, and some of the more recent lava-flows, are shown in the plan, fig. 7.

Mauna Loa, the "Great Mountain," is 13,700 feet high, and its summit is a nearly level plateau, in the centre of which is a huge pit three miles long and a mile and three-quarters broad in the middle. The floor of this pit is in two parts, the outer ends being about 600 feet below the rim, while the central section is about 180 feet lower, as if it had sunk down bodily in consequence of the removal of support below. Many eruptions have taken place from this mountain, but the lava has generally issued from some rent below the summit, and seldom from the crater. The lava seems to rise in a central pipe, and to exert such a pressure on its walls that they give way before it can reach the summit. Thus in 1852 there was first a small issue of lava near the summit, and then a larger outburst from a point about 4,000 feet below it.

In April, 1868, there was an outflow of lava from the southern border of Mauna Loa, at a point only 3,700 feet above the sea. This was preceded by earthquake shocks, which continued for two weeks. The lava was thrown up in a series of jets or fountains at intervals along a line of fissure, and the lava flowed with such rapidity that in a little over two hours the stream had reached the sea, a distance of 10 or 11 miles.

In February, 1877, there was an eruption of six hours duration near the summit of the mountain; lava-fountains were again formed, and a representation of them is given in fig. 8. It was followed by a submarine eruption in Kealakekua Bay. Other more extensive eruptions occurred in 1881 and 1887, producing lava-flows thirty miles in length.

Kilauea (pronounced Kilouea) has usually been described as a subsidiary vent of Mauna Loa, situate on the

Fig. 8. Eruption of Mauna Loa, Hawaii, on February 14, 1877. After a sketch by M. Ballieu, French Consul at Honolulu. Viewed from the north-west.

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after an eruption it is often 1,000 feet deep; the ordinary action in this pit consists of small ebullitions, producing jets of lava which play like fountains to a height of 30 or 40 feet. Sometimes there are only two or three active pools, but in times of greater activity the pools overflow, and the pit fills to within 400 or 500 feet of the rim. An eruption may then be expected; an addition of 400 feet to the column of lava within the crater causes a corresponding increase of pressure, and eventually one or more fractures are produced below the crater, through which the lava makes its way to the surface. During the eruption of 1840 the lava first rose to a great height in Kilauea, and then broke out at several points, one below the other, finally issuing in a continuous stream at a place about 10 miles from the sea, into which it flowed at Nanawale.

Volcanic Islands and Submarine Volcanoes.—A volcanic island may have originated in two ways, it may be either the highest peak of a sunken tract of land, and therefore an island, because the sea has overflowed the ground on which it stands; or, it may have been built up from the sea-bottom, repeated eruptions increasing the height of the volcano till it lifts its head above the waves and becomes an island.

An interesting example of the latter kind of volcanic island was formed in the Mediterranean about 30 miles off the south-west coast of Sicily during the summer of 1831, at a spot where previous soundings had ascertained the depth of the sea to be 600 feet. Its formation was preceded by a violent spouting up of steam and water, and the sea around was covered with floating cinders and shoals of dead fish. At length a small island gradually appeared, having a crater on its summit which ejected steam, ashes, and scoriæ. This crater attained an elevation of nearly 200 feet, with a circumference of about 3 miles, having a circular basin full of boiling water of a dingy red colour.

The island received various names, but is best known by the English one of "Graham's Island," and the French one of "l'Isle Julia." It continued in activity for three weeks and then gradually disappeared. In 1833, two years after its destruction, a dangerous reef remained 11 feet under water, in the centre of which was a black volcanic rock

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bombs here and there. This loose material is being rapidly removed by the waves raised by the constant south-east winds, and its existence as an island will probably be short, unless it contains a hard core or plug of lava. The crater has already been destroyed, and a shallow flat covered by less than 5 fathoms of water extends for a mile to the south of the island. The soundings show that it is separated from Namuka Island by a valley 6,000 feet deep.

Metis Island, 73 miles N.N.E. of Falcon Island, is another volcanic cone that appeared a few years before the latter, but has not yet been surveyed.

Many of the solitary volcanic islands which occur in the midst of the Pacific and Indian Oceans, such as Barren Island (fig. 4), Isle of Bourbon (Réunion), and St. Paul's Island, may have originated in the manner above described.

The following is Jukes' description of St. Paul's: "This island is 3 or 4 miles across, with a curved flat-topped ridge 820 feet high, nearly surrounding a circular crater, into which the sea now flows from one side, and which at the sea-level is almost half a mile in diameter. From the summit of the circular ridge the island slopes gently down towards the sea on all sides, except the [north-]east, where there are vertical cliffs, formed by the sea having cut into the centre of the island so as to gain access to the crater. . . . The entrance was not more than 100 yards wide, and only just deep enough for a boat, but inside there was a depth of 30 fathoms, with a bottom of black mud. . . . At several parts of the beach hot smoking water trickled through the stones. A bank of soundings stretched off the eastern side of the island for a distance of nearly a mile, and a tall detached pinnacle of rock rose from this near the entrance to the crater. This bank was evidently the base from which the rocks that once surrounded the crater, and completed the island, had been removed. The island seemed wholly composed of dark lava in irregular layers, with beds of sand, ashes, and blocks, varying from black to red and cream-coloured. They dipped but slightly outwards, and in one part seemed to dip inwards or towards the crater."[1]

[1] Jukes, "Manual of Geology," second edition, p. 336.

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are ejected into deep water are probably arranged in much the same manner as those which fall on land. Some opportunities have occurred for observing the flow of lava beneath water, and it has been noticed that the crust which rapidly forms over the surface prevents the water from coming in contact with the internal fluid portion of the stream. The escape of heat is also checked by the low conducting power of the crust, and so the interior remains fluid, and continues to flow onward, just at it would do on land. Professor Green has even surmised that, "if the discharge takes place in deep water, it is conceivable that the pressure of the overlying fluid will check the escape both of elastic fluid and of heat from the lava, and so keep it fluid for a longer time, and cause it to spread out in wider and more regular sheets, than if it had flowed out in the open air." [1]

Again, the ash and cinders ejected from such submarine vents will probably arrange themselves on the slopes of the cone, and form beds of tuff and agglomerate, similar to those of sub-aerial origin. But the case is different with the ejections from volcanic islands, because such of these as do not fall on the slopes of the island itself will drop into the shallow waters surrounding it, and will be subjected to the distributive action of the sea-waves, tides, and currents. They will be arranged and stratified on the sea-bottom, and will often be mixed with the other deposits which are there being formed. Arenaceous or calcareous tuffs may thus be produced by the admixture of sand or limestone. Moreover, in all such submarine tuffs, fish, shells, and other marine remains are liable to be enclosed, and will testify by their presence to the conditions under which the stratified masses have been accumulated.

[1] Green, "Physical Geology," second edition, p. 225.

CHAPTER IV.

EARTHQUAKES.

CONNECTION between Volcanoes and Earthquakes.—It has been mentioned that before the bursting out of any great volcanic eruption the neighbourhood is generally shaken by earthquakes. It has also been observed that a succession of earthquakes in a district is often closed by a great volcanic eruption, either in that or in some neighbouring district. These facts suggest that the earthquakes form part of a series of subterranean disturbances which culminate in a volcanic eruption, and that the shocks are due to the exertion of the same force which opens an upward way for the lava till it can be ejected from a volcano. It is not unlikely that both earthquakes and volcanic phenomena are due to the forcible opening of cracks in the earth's crust, the crack starting as a rent or fissure at a great depth.

The connection between volcanoes and earthquakes was exhibited in a remarkable manner by the series of events which took place in and around the Caribbean Sea and Gulf of Mexico at the beginning of this century. From May, 1811, to April, 1812, severe earthquakes were felt in the West India Islands, especially in St. Vincent; violent shocks also occurred in the Mississippi valley, and at Caraccas in Venezuela. Finally, on April 30th, 1812, the volcano of St. Vincent, which had been quiescent for nearly a hundred years, burst into eruption; and so tremendous was the explosion that the noise of it was heard at Caraccas, nearly 500 miles away. This eruption seemed to relieve the subterranean tension, and the earthquakes by which the surrounding regions had been so greatly shaken then

ceased. As the area affected in this case was about 2,000 miles in length, and at least 500 wide, we may infer that the volcano of St. Vincent is connected, not merely with a local reservoir of lava, but with a very large subterranean tract, or, as is most probable, with the liquid substratum which is supposed to underlie the earth's crust (see p. 17).

The connection between the two sets of phenomena is also shown in other ways. Mr. Mallet,[1] who first studied the extent of the areas which are most frequently and violently disturbed by earthquakes, found that these areas form bands of great but variable breadth, which he called seismic bands.[2]

He prepared a map of the world on which the districts known to have been shaken by earthquakes were coloured brown, the tint being made darker and darker in proportion to the frequency and intensity of the shocks which had been experienced at different localities.

A glance at such a map shows that the bands of darkest colour run along the mountain chains on which volcanoes occur; and Mr. Mallet has formulated the following conclusions:—

1. These seismic bands very generally follow the lines of elevation which mark and divide the great oceanic or terroceanic basins of the earth's surface.

2. In so far as these are frequently the lines of mountain chains, and these latter often include lines of volcanic vents, so the seismic bands follow them likewise.

3. The sensible width of the seismic band depends upon the energy developed, and on the accidental geological and topographical conditions along its length.

4. Seismic energy may become sensible at any point of the earth's surface, its efforts being, however, greater as the great volcanic lines of activity are approached.

Professor G. Darwin has pointed out[3] that an earthquake map also suggests the inference that there is a broad band of seismic action which completely encircles

[1] "Catalogue of Earthquakes," Brit. Assoc. Reports, 1847 to 1861.

[2] From *seismos*, an earthquake (Greek); hence also *seismology*, the study of earthquakes.

[3] "Fortnightly Review," February, 1887.

the globe. This traverses Southern Europe and the Mediterranean, Asia Minor and Syria, Persia, India, China, and Japan; crosses the Pacific to Central America and West Indies, and the Atlantic to the Azores, Teneriffe, Portugal, Spain, and N.W. Africa. Although the intensity of the earthquakes felt along this band varies in different parts of it, yet he thinks the evidence is sufficient to show that there is an annular tract of the earth's crust which is specially liable to rupture and consequent disturbance. The other seismic bands, such as those of the Andes and the Malay Archipelago, may be regarded as offshoots more or less at right angles to the main band.

Nature and Origin of Earthquakes.—Mr. Mallet[1] defines an earthquake as a wave of elastic compression, or a succession of such waves travelling through the solid substance of the disturbed country, and it is the emergence of such a wave at the surface of the ground which causes the actual earthquake shock.

This wave is transmitted from a subterranean *centre of impulse* or *focus* (*a* in fig. 12), which Mr. Mallet treats as a rent or fissure, and it proceeds from that focus with equal velocity in every direction. The line along which the wave reaches the surface directly over the centre of impulse (*a b*), Mr. Mallet calls the *seismic vertical*, *b* being called the *epicentrum* or point directly over the centre of impulse, and the concentric lines along which the shock reaches the surface at the same moment he calls the *coseimal lines* (*c c*, *d d*); the wave strikes the surface more and more obliquely as we recede from the line, *a b*, and with less and less force, till it gradually fades away.

In fig. 12, the centre of impulse is represented as a point, and it is assumed that the surrounding rocks are homogeneous, so that the coseimal lines are circles. In reality, however, the centre of impulse must generally be a narrow fissure of some length, and the impulse will generate waves proceeding outwards from the surface of the fissure in ellipsoidal shells, the coseimal lines being ovals whose major axes are at right angles to the plane of the fissure. The variation in the density and elasticity of the rocks

[1] "First Principles of Observational Seismology."

through which the wave passes, also interferes with the regularity of the coseimal lines, and the passage of the wave from one kind of rock to another causes refractions, so that the actual form of the wave at the surface is complex and irregular.

The earth-wave travels most rapidly through hard and compact rocks, less rapidly through soft and incoherent beds. Mr. Mallet has experimented by exploding gunpowder and calculating the velocity of the shock so produced in different rocks. He found that the wave traversed—

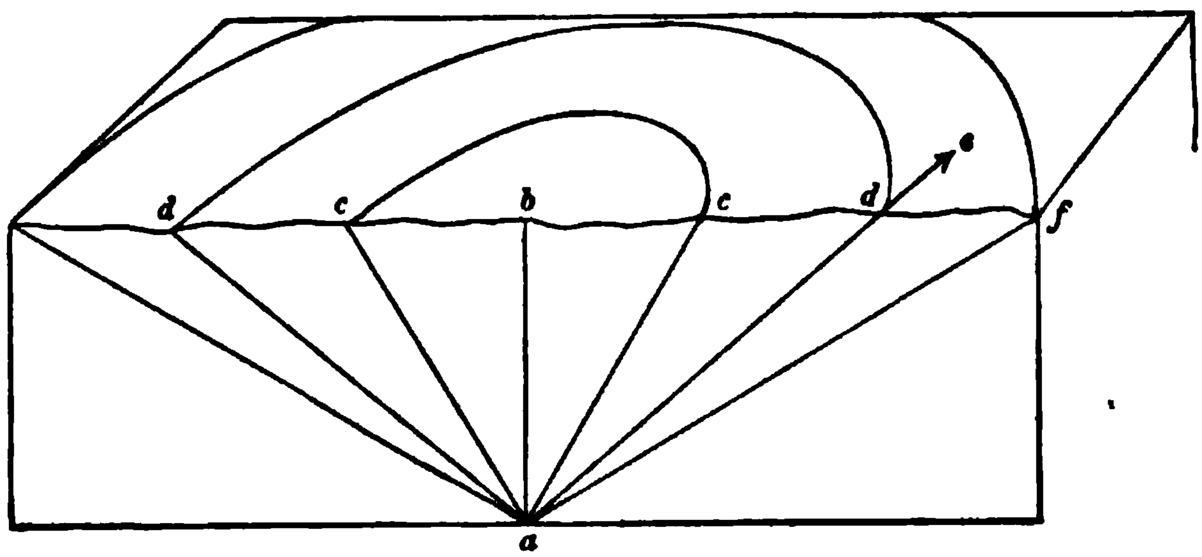

Fig. 12. Diagram of the propagation of an Earthquake Wave.

Solid granite	at a rate of	1,665	feet	per second.
Shattered granite	„	1,306	„	„
Slate „	„	1,089	„	„
Wet sand „	„	825	„	„

By observing the direction of fissures and by the use of instruments called *seismometers*, Mr. Mallet believed it possible to determine the direction and the angle of emergence of the wave-path, and thus to calculate the position and depth of the centre of impulse from which the wave proceeded. By this method Mr. Mallet calculated that the centre from which the shock of the great Calabrian earthquake in 1857 proceeded, was beneath a spot about 60 miles E.S.E. of Naples, and at a depth of about 5 miles from the surface. He assigned 30 geographical miles, or 185,000 feet, as the limit of depth at which any earthquake originates.

It has, however, been pointed out that the passage of a shock through loose soils and surface rocks cannot be compared with that through dense, compact, and deeply buried rocks; and that the wave is chiefly propagated through such deeply buried rocks. The actual rate of propagation must depend on the density and elasticity of the materials through which it passes; the rate of the passage of compressional waves through a bar of steel has been estimated at 21,000 feet per second, and by comparing the density and elasticity of very dense rocks with the same properties of steel, the rate of passage through such rocks has been calculated to be about 18,400 feet, or 3·4 miles per second.[1]

It is a remarkable fact that in the case of the Charleston earthquake of 1887 six careful time records, taken at distances of 300 to 645 miles, gave an average result of 3·3 miles per second as the rate of speed. This is a much higher speed than has hitherto been observed in European earthquakes, which have given results varying only from 660 to 2,860 feet per second. The discrepancy remains to be accounted for; it seems too great to be explained by errors of observation, and the speed of the Charleston earthquake wave may possibly be due to the greater depth of its point of origin.

It is not always possible, however, to ascertain the angle of emergence, and another method has recently been suggested by the investigators of the Charleston earthquake, which promises to give more accurate results. By this method the depth of the seismic focus at Charleston in 1887 was calculated to be about 12 miles.

Messrs. Dutton and Hayden believe that few earthquakes originate at a greater depth than this. They point out that earthquakes differ in energy and in depth of origin, the intensity of the shock at the surface depending on the energy developed at the focus, and on the distance of that focus from the surface. An earthquake of great intensity may be due to the focus being near the surface, or to the development of great energy at the focus, or to both combined. It follows also that the radial distance to which

[1] "Investigation of the Charleston Earthquake," by C. E. Dutton and E. Hayden, "Nature," July 28th, 1887, p. 302.

the shock is transmitted is the best measure of the total energy of the shock. If, therefore, in comparing the effects of two earthquakes, we find that the intensity of the shock at the epicentrum was about the same, but that one was felt over a much wider area than the other, we may at once infer that the focus of the one was more deeply seated than that of the other. Now the Charleston earthquake was felt at a distance of 1,000 miles from the centre, and yet its intensity at the epicentrum was relatively low; hence these observers conclude that the depth at which it originated was relatively great. This depth they found to be about twelve miles; they therefore regard this as a great depth, and suggest that estimates of the depth of earthquake foci exceeding this require re-investigation. ("Nature," July, 1887, p. 300.)

Phenomena and Effects of Earthquakes.—The phenomena attendant upon an earthquake shock vary according as the centre of impulse is under the land or under the sea. In the first case waves are only progagated through the earth and through the air: in the second case the waves are communicated to three media, viz., earth, air, and water. Moreover, sound-waves appear to be carried through the earth and the sea, as well as through the air, so that if the shock originates under the sea, an observer standing near the shore will perceive the following succession of phenomena.

1. A rumbling noise, heard apparently through the feet; this being the sound-wave through the earth, which is said to travel at a rate of 11,000 feet per second.

2. Another sound caused by the sound-wave through the air, which travels at the rate of 4,700 feet per second.

3. The earth-wave, bearing with it a small forced sea-wave; its velocity varying, as already stated, from about 800 to 1,600 feet per second (mean rate about 1,200 feet).

4. A third sound produced by the sound-wave through the water, which is carried 1,138 feet per second, and therefore is sometimes heard at the same time as the earth-wave is felt.

5. The great sea-wave, the sea being first sucked back for some distance from the shore, and then returning as a wall of water from 15 to 20 feet high, rolling in far over

the land and washing down everything before it. The first is often followed by smaller waves.

The velocity of the sea-wave depends upon the depth of the water through which it is propagated; it travels through deep water much faster than through shallow water near the land. Thus the sea-wave of the Lisbon earthquake in 1755 travelled to London at a little over 2 miles a minute, but crossed the Atlantic to Barbados at a rate of about 5 miles per minute. The wave which travelled across the Pacific from Japan to California in 1854 had an average velocity of 6·1 miles per minute.[1]

The surface effects of an earthquake wave are more destructive when it traverses soft rocks because the cracks which it produces at the surface are kept open for a longer time, and allow buildings to subside; while in hard rocks these fissures are narrower and close more quickly, so that less displacement is caused. When the wave passes from compact into loose rocks, there is often a complex reflection and reverberation of shocks which results in a destructive shivering of the surface.

If the angle of emergence is low, the difficulty which the wave finds in passing from hard into overlying soft rocks is such that a very small shock is propagated through the latter. Thus the Lisbon earthquake was felt in Scotland; but not in England, and the reason is supposed to be that the wave travelled through the hard rocks at a great depth below the ground, and the slight shock communicated to the thick mass of softer rocks which form the greater part of England died away before it reached the surface.

Instances of Earthquakes.—*Italy.*—The earthquakes which convulsed Calabria in 1783 were remarkable for the number of separate shocks (949) that occurred during the year, and for the great disturbances and changes which they produced on the surface of the ground. The area over which these shocks exerted their most violent effects was not more than 500 square miles, but they were peeceptible over a great part of Sicily, and as far north as Naples.

[1] From this it has been calculated that the mean depth of the body of water through which it moved, viz., the North Pacific, was 14,190 feet.

In some of the Calabrian towns the pavements were thrown into the air and reversed so as to lie bottom upwards. Long undulating fissures were formed, some of which remained open, and some gradually closed up again. The wells and springs were violently disturbed, and in some places circular cavities were opened from which water escaped, and which afterwards remained in the form of pools.[1]

In the town of Terranuova some houses were elevated above their former level, while others sank below it, and one tower of solid masonry was divided into two parts by a crack, on one side of which the building was elevated several feet above the other part. This vertical shift was rendered apparent by the discontinuity of the courses of stone, which presented a counterpart of the dislocation which must have been produced in the rocks below, and which is termed a *fault* by geologists.

Great mases of earth and rock slid down from the sides of the valleys, and some of these landslips dammed up the rivers, and gave rise to new lakes. Thus enormous masses of land were detached from each side of the deep valley or ravine of Terranuova, and blocked up the course of the river, causing the formation of a large lake. It is stated that about fifty such lakes were formed at this time; some of these were permanent, the course of the streams being altered, but others were gradually drained by the water overflowing and cutting a channel through the barrier. Along the sea-coast huge masses were detached from the cliffs, especially at Scilla and at Gian Greco in the Straits of Messina, where a continuous line of cliff was thrown down for the length of a mile.

The Neapolitan earthquake of 1857 was one of great intensity, the shocks causing much displacement of the ground, which was in many places rent and fissured. Some of these fissures remained open after the cessation of the shocks, and fig. 13 represents a fissure observed by Mr. R. Mallet in the gorge of Bella near Naples after that earthquake. It will be observed that it exhibits a certain amount of vertical movement, one side of the fissure being higher than the other.

[1] See the account in Lyell's "Principles," vol. ii. ch. xxix.

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been calculated, according to Mr. Mallet, at 100 feet, which he says would give a velocity of shock equal to 80 feet per second.

The centre of the disturbance seems to have been the volcano Tunguragua, and the district most violently shaken measured 120 miles from north to south, and 60 miles from east to west, but the shocks were felt far beyond these limits. Riobamba and all the other towns within this area were destroyed. The ground about Tunguragua opened into enormous clefts, from which issued volumes of water and stinking mud, forming lakes in many places of considerable size.[1]

Another of the great earthquakes which so frequently shake the western coast of South America happened on the 20th of February, 1835. It was felt in all places between Chiloe on the south and Copiapo on the north, a distance of more than 1,000 miles, and between the city of Mendoza on the east and the island of Juan Fernandez on the west, a distance of at least 600 miles. Admiral Fitzroy, who was at Talcahuano, the port of Concepcion, says that after the earthquake there was a belt of coast 4 or 5 feet in height, which, even at high water, showed beds of dead mussels, limpets, and withered sea-weed, all still adhering to the rocks. This raised beach gradually sank again until the part above high-water mark was not more than 2 feet high. He also visited the neighbouring island of Santa Maria, where he found that the following changes had taken place. "It appeared that the southern extremity of the island had been raised 8 feet, the middle 9, and the northern end upwards of 10 feet. On steep rocks, where vertical measures could be correctly taken, beds of dead mussels were found 10 feet above high-water mark. An extensive rocky flat lies around the northern parts of Santa Maria. Before the earthquake this flat was covered by the sea, some projecting rocks only showing themselves. Now the whole flat is exposed, and square acres of it are covered with dead shell-fish, the stench arising from which is abominable."[2]

[1] Humboldt's "Voyage," p. 317.

[2] Phil. Trans., 1826, and Lyell's "Principles," tenth edition, vol. ii. p. 93.

Speaking of the same earthquake the late Dr. Darwin says: [1]—"The island of Quiriquina plainly showed the overwhelming power of the earthquake. The ground in many parts was fissured in north and south lines, perhaps caused by the yielding of the parallel and steep sides of this narrow island. Some of the fissures near the cliffs were a yard wide. Many enormous masses had already fallen on the beach; and the inhabitants thought that when the rains commenced far greater slips would happen. The effect of the vibration on the hard primary slate, which composed the foundation of the island, was still more curious: the superficial parts of some narrow ridges were as completely shivered as if they had been blasted by gunpowder. This effect, which was rendered conspicuous by the fresh fractures and displaced soil, must be confined to near the surface, for otherwise there would not exist a block of solid rock throughout Chile; nor is this improbable, as it is known that the surface of a vibrating body is affected differently from the central part. It is, perhaps, owing to this same reason, that earthquakes do not cause quite such terrific havoc within deep mines as would be expected. I believe this convulsion has been more effectual in lessening the size of the island of Quiriquina, than the ordinary wear-and-tear of the sea and weather during the course of a whole century."

North America.—The earthquake which originated near Charleston (Carolina) in 1887 has been carefully investigated by Capt. Dutton and Dr. Hayden, and some of their observations have already been mentioned. This earthquake was felt at a distance of 1,000 miles in more than one direction, but there were several tracts where the intensity of the shock was feeble compared with its effect on the surrounding areas. Two of these are quite isolated, the third is a tongue-shaped tract over the north-west part of the Appalachian region in Virginia. The cause of these tracts being less shaken is not clear. The tract over which the most forcible shocks occurred was an elliptical area about 26 miles long and 18 wide; the major axis of this was not a straight line, but a curve, with its concave

[1] "Voyage of the Beagle," edition of 1860, p. 393.

side towards Charleston, and lying about 14 miles from that city. Along this line there were three points which had the characters of epicentra, indicating apparently three distinct foci or centres from which three separate shocks proceeded. One of these was computed to lie at about 12 miles from the surface, and the others appeared to be at the same depth.

New Zealand.—A great earthquake occurred in New Zealand in 1855, during which a tract of land comprising 4,600 square miles is believed to have been permanently upraised; Sir C. Lyell states on the authority of Mr. Edward Roberts, R.E.,[1] that the amount of elevation increased eastward and attained its maximum along the Rimutaka range near Port Nicholson, where the elevation was 9 feet. The land on the west side of these mountains,

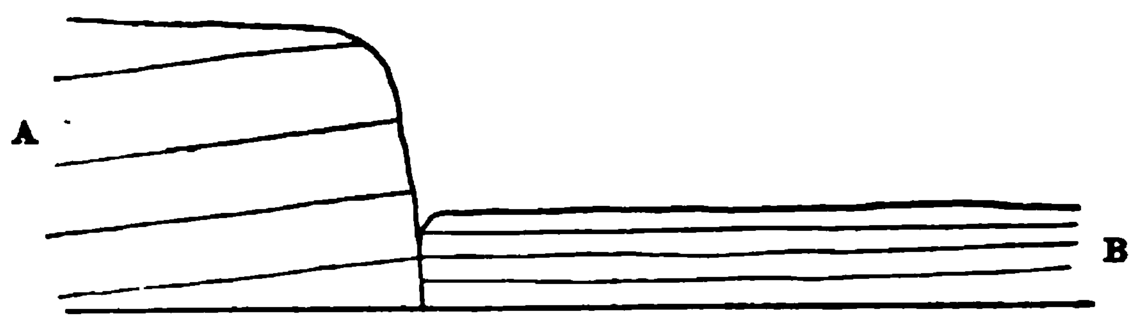

Fig. 14. Fracture and upheaval in New Zealand, after Lyell.

forming the plain of Wairarapa, was not raised at all, the vertical movement ceasing abruptly along the base of the hills, and forming a line of fault or fracture which was traced for a distance of 90 miles.

The course of the fracture along the base of the hills was rendered visible by a nearly perpendicular cliff of fresh aspect about 9 feet in height. It was marked moreover in many places by fissures from 6 to 9 feet broad, filled here and there with soft mud and loose earth. The relations of the rocks on either side of this dislocation are indicated in the diagram, fig. 14, the hard rocks A being elevated, while the newer, B, remained horizontal. Previous to the earthquake there had been no room to pass between the sea and the base of the perpendicular cliff in which the

[1] Lyell's "Principles," tenth edition, vol. ii. p. 85.

Rimutaka range terminates in Cook's Strait, except for a short time at low water; "but immediately after the upheaval a gently sloping raised beach, more than 100 feet wide, was laid dry, affording ample space at all states of the tide for the passage of man and beast."[1]

Summary of Surface Effects produced by Earthquakes.—1. *Heaving of the Ground.*—The peculiar motion felt during an earthquake results from a combination of two kinds of movements; an upward shock or jerk, and a progressive wave or rolling movement, and it is this combination which produces such destructive results. The upward shock opens the cracks and joints in all rocks as well as in the walls of buildings, and the undulating movement rocks them to and fro, shaking down buildings and hurling large masses from sea-cliffs and valley-sides.

2. *Damming up of Rivers.*—The masses of earth and rock thus detached from the sides of a valley often block up the stream at the bottom, and cause the formation of a lake. If the barrier remain, and the stream is diverted into a new course, the lake may be permanent; but if the dam gives way and the pent-up waters escape, the lake is drained and destructive floods are caused.

3. *Opening of Cracks and Fissures.*—Instances of such fissures have been mentioned. They sometimes open and shut again rapidly as the undulating movement passes on, but frequently remain as open clefts or chasms, varying in length from a few feet to as many miles. Sometimes one side of the rent is at a higher level than the other, such a dislocation forming a fault in the rocks below. Rivers are occasionally engulfed in these fissures, and pursue an underground course for some distance.

4. *Permanent Changes of Level.*—These are the most important geological results which earthquakes produce, for, as already stated, the solid land is sometimes raised or lowered several feet at a time over large areas. The extent of such movements is best seen along the sea-shore, where in the one case a new strip of land may be added to the coast-line by the elevation of the beach and adjacent sea-bottom, or in the other case, if depression has taken place,

[1] Lyell, *op. cit.* vol. ii. p. 86.

the sea may have overflowed its ancient limits and encroached upon the land. Inland the slope of water-courses is often altered, the rapidity of the current being increased or diminished according to circumstances, and sometimes rivers are diverted from their former channels. An instance of this in South America is mentioned by Dr. Darwin, on the authority of a resident engineer.

"Travelling from Casma to Huaraz (not very distant from Lima), Mr. Gill found a plain covered with ruins and marks of ancient cultivation, but now quite barren. Near it was the dry course of a considerable river, whence the water for irrigation had formerly been conducted. There was nothing in the appearance of the water-course to indicate that the river had not flowed there a few years previously; in some parts, beds of sand and gravel were spread out; in others, the solid rock had been worn into a broad channel, which in one spot was about 40 yards in breadth, and 8 feet deep. It is self-evident that a person following up the course of a stream, will always ascend at a greater or less inclination; Mr. Gill, therefore, was much astonished, when walking up the bed of this ancient river, to find himself suddenly going down hill. He imagined that the downward slope had a fall of about 40 or 50 feet perpendicular. We here have unequivocal evidence that a ridge had been uplifted right across the old bed of a stream. From the moment the river-course was thus arched, the water must necessarily have been thrown back and a new channel formed. From that moment also, the neigbouring plain must have lost its fertilizing stream, and become a desert." ("Voyage of the Beagle," edition 1860, p. 359.)

5. *Alternating Movements.*—One of the most interesting examples of alternating movements of subsidence and upheaval in a volcanic district is that afforded by the remains of the celebrated temple of Jupiter Serapis at Puzzuoli on the Bay of Baiæ. These movements may not all have been accomplished suddenly during earthquakes, but there is reason to believe that some of them were, and though at times the movement may have been slow and gradual it was evidently due to the same local causes.

The ruins of this building were discovered about the middle of last century, and excavations disclosed a square

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The temple area was filled with a succession of stratified deposits, consisting of marine and fresh-water limestones with two layers of volcanic tuff, ejected, probably, from the neighbouring crater of the Solfatara. These beds concealed the lower part of the columns up to the base of the perforated band, and the perforations were thus evidently made during a subsequent subsidence of 9 or 10 feet; the lower portion being protected from their attacks by the accumulation of sediment, and the upper part at the same time projecting above the surface of the sea.

The upper limit of the perforations was, in 1828, about 23 feet above the level of the sea, so that there had been an elevation of the whole area to at least this extent. This upheaval appears to have taken place during the 16th century, for two documents are cited in which Ferdinand and Isabella of Spain grant to the University of Pozzuoli a portion of land "where the sea is drying up" (1503), and again, "where the ground is dried up" (1511). This seems to indicate that a slow and gradual upward movement was taking place during this period, but it is probable that the principal elevation took place at the time of the great eruption of Monte Nuovo in 1538. Two eye-witnesses of this convulsion declare that the sea then abandoned a considerable tract of the shore.[1]

The oscillations of level which appear to have occurred in this area during historic times may therefore be thus summarized:—

1. Subsidence of 5 feet between the two pavements.
2. Period of rest, the temple built.
3. Gradual subsidence of 12 feet, and deposition of sediment; subsidence continued for 9 feet without deposition.
4. Period of rest, and perforations made in the columns by boring molluscs.
5. Gradual upheaval to extent of more than 23 feet.
6. Slight subsidence again at the beginning of the present century.

[1] "Principles of Geology," tenth edition, vol. ii. p. 174.

CHAPTER V.

ELEVATION AND DEPRESSION OF LAND.

WE have already seen that movements of elevation and depression often take place during earthquakes, and that considerable tracts of land have been permanently raised or lowered in this way. We have now to learn that in some parts of the world, where no great earthquakes have happened during the periods of history, there have, nevertheless, been similar changes in the level of the land, the movements often affecting large areas of the earth's crust, and taking place quite gradually and imperceptibly, not by jumps and starts as in the case of earthquakes.

There is also reason to believe that both kinds of movement may take place at different times in the same area, slow and imperceptible changes occurring in the intervals between the sudden shocks; there is proof, moreover, that intervals of rest alternate with epochs of movement, and that sometimes movements of elevation have succeeded movements of depression in the same area.

The signs and evidences by which we may know that a movement of upheaval or one of subsidence has taken place in a given district are not equally obvious in both cases. When land is lifted up above the sea, it generally brings up with it some proofs of its having once been under water; but when a coast-line is sinking below the sea-level, the fact is less easily proved, because the subsidence soon removes its surface from our inspection. There are, however, facts of various kinds which are accepted as sufficient evidence of subsidence, and others which are proofs that elevation has taken place. It will be useful, therefore, if we tabulate the indications which can be adduced as evidence for such

changes of level, and exemplify each kind of testimony by appropriate instances.

Proofs of Elevation.

1. *Testimony of Human Erections.*—When ancient moles and harbour works have been raised above the level of the sea, they afford very convincing proofs of upheaval, but it is only in countries where man has resided for many centuries that such testimony can be looked for. The island of Crete or Candia is, however, a case in point. This island is about 135 miles long, and Captain Spratt, R.N., ascertained that its western end has been uplifted 17 feet above its ancient level, while a part of the southern coast has risen more than 27 feet, so that the docks of the ancient Greek ports are now above water, as well as masses of limestone rock drilled by *lithodomi*. At the same time, the eastern part of the island has sunk many feet, causing the submergence of several Greek towns, the ruins of which are still visible under the water.

2. *Testimony of raised Rocks and Islands.*—The coasts of Norway and Sweden consist chiefly of hard rocks, and are fringed with numerous islets; and as there are no tides in the Baltic Sea, conditions are there peculiarly favourable for making exact observations on the relative level of land and sea.

South of Stockholm no rise is perceptible, and it appears that there has even been depression, but north of that city the elevation is sufficiently obvious. It was observed early in the last century by Celsius, who remarks that "several rocks on the shores of the Baltic which are now above water (A.D. 1730), were not long before sunken rocks, and dangerous to navigators; one especially, which in the year 1680 was on a level with the surface of the water, is 20½ Swedish metres above it (60 English feet). From an inscription near Aspo, in the Lake Maelar, which communicates with the Baltic, engraved, as it is supposed, above 500 years ago, the land appears to have risen no less than 13 Swedish feet (12·66 British)."[1]

[1] Playfair's "Illustrations of the Huttonian Theory," edition 1822, p. 436.

Celsius' statements excited so much attention and discussion, that lines or grooves, together with the date of the year, were cut in the rocks at different places along the Baltic to indicate the ordinary level of the water on a calm day. In 1820-21 all these marks were examined by the officers of the pilot establishment of Sweden, and they reported that the level of the Baltic was certainly lower, relatively to the land, than it had been, but that the amount of change had not been everywhere the same. During their survey they also cut new marks for the guidance of future observers.

Sir Charles Lyell visited Sweden in 1834, with the view of determining this question, and specially examined the marks cut on the shores of the Gulf of Bothnia. He found that the level of the sea at that time was several inches below the marks cut by the pilots, and from 2 to 3 feet below the more ancient marks. Thus at Gefle, north of Stockholm, for example, he found that the land had risen about 4 inches in the interval between 1820 and 1834, and, consequently, that the upward movement had proceeded at the rate of about $2\frac{1}{2}$ feet in a century. He ascertained also that the testimony of the inhabitants, both on the eastern coasts and on the western near Gothenburg, agreed with that of their ancestors—viz., that the low rocks, both on the shore of the mainland and on the islands, are more and more exposed to view.[1]

3. *Testimony of Marine Shells.*—The evidence already cited refers only to recent historic times, but there are other and convincing proofs that the elevation of Scandinavia has been going on for many centuries, and that similar upward movements have taken place in many other parts of the world. The first of these proofs is the existence of beds of sea-shells, sometimes many miles in the interior of the country, and often at a height of several hundred feet above the present level of the sea.

In Sweden, for example, such banks containing recent marine shells have been met with at many localities, and at various heights, from 10 to 200 feet. Between Stockholm and Gefle there are deposits containing shells of the

[1] "Principles of Geology," tenth edition, vol. ii. p. 190-1.

same species as now inhabit the brackish waters of the Bothnia Gulf up to elevations of 100 feet. Lyell traced these beds inland to a point on the southern shores of Lake Maeler, about 70 miles from the sea; and M. Erdman has subsequently traced them to Linde, a distance of 130 miles from the sea, where they occur at a height of 230 feet.

Similar beds of sea-shells have also been found at an elevation of 200 feet on the northern border of Lake Wener, 50 miles from the western coast, so that a very large area must have been added to Sweden in comparatively recent times.

Uddevalla, near Wenersburg, is another place where beds of recent shells have been found; and here M. Alex. Brongniart, on removing part of the shell deposit, perceived that the underlying surface was covered with barnacles still firmly adhering to the rocks. This observation was verified by Sir C. Lyell by a similar discovery at another spot near Uddevalla.[1]

In parts of Norway deposits containing sea-shells of recent species occur at elevations of 600 and even 700 feet, according to Mr. Torell.

Dr. Darwin has described the beds of sea-shells which he found at various heights above the sea along the west coast of South America. Commencing at Tierra del Fuego, he traced them for a distance of 2,075 miles along the western coast, and at various elevations, from 300 to 1,300 feet above the sea. They occur in connection with the raised beaches presently to be mentioned; and Darwin remarks that the shells at the lower levels were fresh, but that those at the greater heights were brittle and decomposed from prolonged exposure to the weather. Those near Valparaiso, where he found them up to a height of 1,300 feet, were embedded in a reddish mould, having a guano-like smell, and in which minute fragments of sea-urchins and other marine animals could be detected.

4. *Testimony of Raised Beaches.*—A beach may be defined as an accumulation of sand or shingle piled up by the action of the waves against a shore line. Wherever the shore is backed by a range of cliffs a beach is formed along their

[1] "Principles," vol. ii. p. 192.

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At the base of the cliffs, and bounding the modern beach, there is a low wall or terrace of chalk, and upon this rests a bed of sand (*o*, in fig. 19), of irregular thickness and variable extent. From this sand marine shells and the jaw of a whale have been obtained. Upon this sand is a bed of loose shingle similar to that of the present beach, though the pebbles of which it consists are not all flints. In this ancient shingle the teeth and bones of various extinct animals have been discovered.

The rest of the cliff above the shingle bed consists of a mass of chalk rubble and loam, obscurely stratified, and varying in thickness from 50 to 120 feet. This is a terrestial deposit, and was named the "Elephant bed" by Dr. Mantell, on account of its containing so many teeth and bones of the extinct elephant, known as the mammoth, together with the remains of other animals, such as the rhinoceros, horse, deer, and oxen.

These facts demonstrate the following series of changes in the relative level of land and sea:—

1. The chalk terrace on which the sand and shingle rest was at the sea-level for a long period, and a beach was formed at the base of the chalk cliffs then existing.

2. The land was elevated, probably, to a higher level than that at which it now stands, and the Elephant bed was accumulated in an old hollow or valley.

3. The present cliffs, with the modern beach at their base, have been formed by the action of the sea, which will be described in a future chapter.

Scotland.—Well-marked terraces with raised beaches have been traced at intervals along the Scottish coasts, four or five sometimes occurring one above the other, at heights of 25, 40, 60, 75, and 100 feet above the present high-water mark.[1] The lowest of these is thus described by Professor A. Geikie:—"For many miles on both the eastern and western sides of Scotland a flat platform, but slightly raised above the sea, winds along the coast, bounded on the outer edge by the line of high water, on the inner by a more or less precipitous bank of clay or rock. Most of

[1] "Good Words," 1868, p. 62. See also "The Scenery and Geology of Scotland," second edition, 1887, p. 38.

the seaport towns are built upon this level terrace, and it furnishes an admirable route for roads and railways which skirt the shore. It consists of stratified sand and gravel, sometimes full of sea-shells, and arranged after the same fashion in which similar materials are now being deposited upon the present beach. The platform is in truth an old sea-beach, and marks a time when the land was 20 or 30 feet lower than it is to-day, and when the sea broke against the line of steep slope or cliff which now rises as a green leafy bank along the inner edge of the beach." The platform is covered with meadows and cornfields which run up to the base of the cliffs. (Fig. 17.)

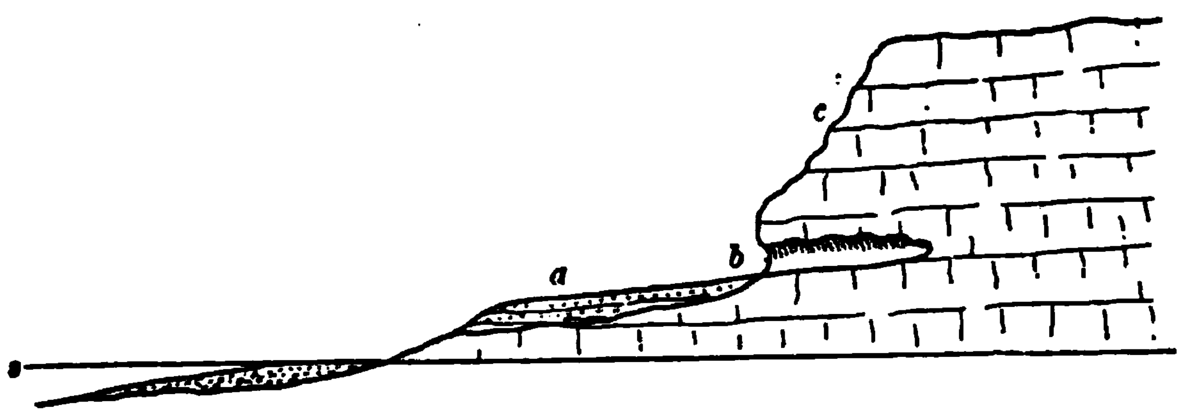

Fig. 20.

a, raised beach. *c*, cliff.
b, cave. *s s*, high-water mark.

5. *Testimony of Old Sea-Caves.*—The formation of caves by the action of the sea-waves beating against a line of cliffs will be described in a future chapter. The caves are excavated at the foot of the cliffs, and consequently, if the coast is afterwards elevated, these caves will remain as evidence of the level at which the land formerly stood. Excellent examples of such old cliffs and caves occur at various heights along the rocky coasts of Scotland up to a level of 100 feet above the sea, and are often associated with the raised beaches (as in fig. 20).

Along the coast of Cantyre there are numerous caves at the foot of the cliffs which border the 25 foot beach, which is thus described by Professor Hull:[1]—"All along the coast the ancient sea-margin may be traced by a line of

[1] "Geol. Mag.," vol. iii. p. 6.

cliffs of various degrees of steepness according to the nature of the rock. . . . From the base of this cliff a slightly shelving terrace extends to the present sea-margin, on which most of the villages are built. . . . The caves whch are found at intervals all round the coast, and which form a range of natural rock-hewn compartments at a level of 10 to 30 feet above the present tidal limits, are perhaps the most convincing of all the various evidences of ancient sea-action." Some of these caves near Campbelton and Neill are specially described, and extend into the cliff for a distance of 120 feet.

Proofs of Depression.

It has already been remarked that the proofs of the submergence of land are not generally so obvious as those of its elevation; so that to a careless observer elevation will appear to have been more general than depression in most parts of the earth. In some cases, however, there is direct evidence in the actual submergence of buildings and former land-surfaces; and in other cases the fact of depression can be as certainly deduced from the position of the river valleys in relation to the present level of the sea.

1. *Testimony of Human Erections.*—Where the land has been sinking for a long time, the ruins of ancient towns and buildings are sometimes visible beneath the sea; as, for instance, at the east end of Candia, mentioned on p. 66. It is necessary, however, to point out that the mere encroachment of the sea upon the land cannot be accepted as proof of subsidence, because, as will be explained in a future chapter, the waves can cut back a coast line, and cause the successive disappearance of fields, houses, and villages, without being aided by any movement of depression. It is requisite, therefore, that the relation of the buildings to the sea should be such as to demonstrate that an actual change of level has taken place.

This is the case on the western coast of Greenland, which was surveyed by Captain Graah and Dr. Pingel between the years 1823 and 1832. They arrived at the conclusion

that the land had been sinking for the last four centuries between Igaliko, in 60° 43′ N. lat., and Disco in 69°, a space of 600 miles. "Ancient buildings on low rocky islands have been gradually submerged, and experience has taught the aboriginal Greenlander never to build his hut near the water's edge. In one case the Moravian settlers have been obliged more than once to move inland the poles upon which their large boats were set, and the old poles still remain beneath the water as silent witnesses of the change."[1] Again, in Scania, the most southerly part of Sweden, there is similar evidence that the land is sinking. In many of the seaport towns some of the streets are below the level of high-water mark, and ancient streets have been found at a still lower level. Thus, at Malmö, one of the present streets is overflowed by the waters of the Baltic when the wind is high, and excavations made some years ago disclosed an ancient street at a depth of 8 feet below the present one. There is a large stone at Trelleborg, the distance between which and the sea-margin was measured by Linnæus in 1749, and in 1836 it was found to be 100 feet nearer the water's edge than it was eighty-seven years before.

3. *Testimony of Submerged Forests.*—When a tract of land is depressed beneath the sea, its superficial layer is generally removed by the action of the waves; but under favourable circumstances, in sheltered bays and estuaries, or by the formation of sand dunes, the old terrestrial surface is sometimes preserved, and the stumps of old trees are often seen on the shore at and below present low-water mark. De la Beche thus describes the remains of such an old land surface exposed along the south-west coast of England.[2] "Round the shores of Devon, Cornwall, and West Somerset, a vegetable accumulation, consisting of plants of the same species as those which now grow freely on the adjoining land, is frequently discovered, occurring as a bed at the mouths of valleys, at the bottoms of sheltered bays, and in front of and under low tracts of land, the seaward side of which dips beneath the present level of the sea."

[1] Lyell, "Principles of Geology," ii. p. 196.
[2] "Geological Report on Devon and Cornwall," p. 420.

Similar beds of peaty matter occur at numerous points all round the coasts of Great Britain and Ireland, proving that the last movement to which these islands have been subjected, was one of depression. Two instances may be adduced:—

1. In the harbour of Holyhead a bed of peat 3 feet thick, with the stumps and roots of trees, is exposed at low water, and stretches upward to a slight elevation above the sea, where the excavations made for the railway in 1849, showed that it was covered by stiff blue clay, and brought to light two perfect heads of the extinct elephant known as the Mammoth.

2. A submerged forest of large exent exists off the north coast of Norfolk from Hunstanton to Brancaster Bay. The portion exposed at low-water, north of Hunstanton cliff end, is about a mile and a half from high-water mark, and consists of a thick bed of black peaty matter, composed of small twigs, branches, leaves, and other vegetable remains matted together, and enclosing the trunks, stumps, and roots of large timber trees. The forest here occupies an area of at least 500 or 600 acres, and among the roots are occasionally found the remains of deer and oxen, proving that these animals once roamed through the forest. Possibly also they may have been hunted here by the early inhabitants of Britain, for a flint-celt or axe was found embedded by its cutting-edge for a depth of an inch and a half in the trunk of one of the trees. A similar forest-bed is found along parts of the Lincolnshire coast, and is overlaid by the recent clays of the marshland.[1]

3. *Testimony of Buried Valleys.*—That rivers make their own valleys will be proved in a subsequent chapter, but their excavating power generally ceases long before they reach the sea, and in no case can a river deepen its channel more than a few feet below the low-tide level. When, therefore, borings disclose the existence of valleys, the rocky bottoms of which are 50, 70, or 100 feet below the sea-level, and which are filled up with deposits of gravel, sand, and clay, we may conclude that they are parts of an

[1] For other examples of submerged forests, see "Geol. Mag.," vol. vii. p. 164, and Dec. 2, vol. iii. p. 491. "Quart. Journ. Geol. Soc.," xxxiv. p. 447.

old land surface which has sunk beneath the sea. When such valleys were formed the land must have stood at a higher level, the sea must have been further off, and the valley floor must have been above its level; consequently, if the bottom of the valley is now 100 feet below the sea-level, it is proof that there has been a subsidence of at least that extent.

Such buried valleys are not uncommon in the British islands; for instance, the rivers Yare and Waveney, in Norfolk, flow through flat alluvial tracts for many miles before they reach the sea, the width of the valleys being great in proportion to their apparent depth; though the real depth of the original valley is in accordance with this width. In the valley of the Yare, at Wroxham Bridge,

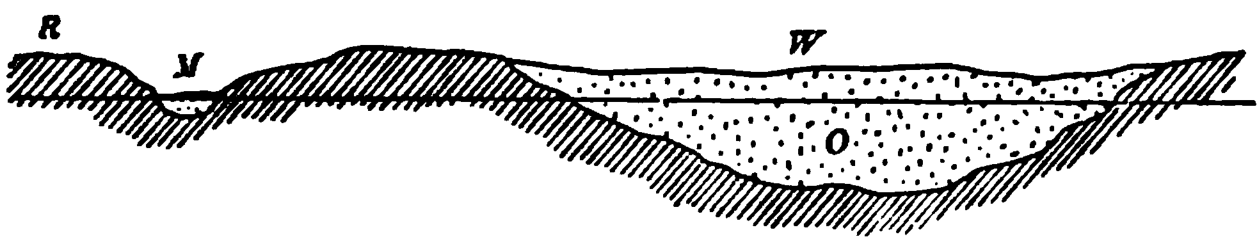

Fig. 21. The buried Valley of the Mersey.

Horizontal scale, 2 inches to a mile. M, present valley; O, ancient valley filled with drift; W, site of Widnes; R, site of Runcorn; S S, sea-level.

there is as much as 70 feet of detrital matter between the present alluvial level and the chalk which forms the bottom of the actual valley.

Borings at the mouth of the river Tees prove that the bottom of the ancient valley is about 200 feet below Ordnance datum, or mean sea-level; and a boring near the mouth of the Tyne was carried to a depth of 124 feet without reaching the rock-bed of the valley.

Again, borings at Widnes, on the north side of the estuary of the Mersey, have shown that there is a buried valley nearly a mile in breadth and with an extreme depth of 163 feet from the present surface, and 141 feet below Ordnance datum. Fig. 21, which is copied from that drawn by Mr. Mellard Reade, shows the comparative size of the present and the ancient valley of the Mersey between Runcorn and Widnes.

Similar old valleys and river channels have been dis-

covered in Scotland, so completely buried by subsequent deposits that there is no indication of their presence on the surface; in some cases the sites of these buried valleys are covered by low hills or mounds more than 100 feet high, so that the courses of the ancient rivers must have been very different from the present streams.

One of these old river channels has been traced from Kilsith in Stirlingshire to Grangemouth on the Firth of Forth. The surface of the ground at Kilsith is now 160 feet above the sea, and the old valley bottom lies at a depth of 120 feet, or 40 feet above the sea; thence it slopes gradually eastward till at Grangemouth the old channel is 260 feet below the sea-level.[1]

At the time, therefore, when this channel was occupied by the river which made it, the land must have been at least 260 feet higher out of the sea than it is now, an elevation which would be sufficient to unite the British islands to the continent of Europe.

4. *Testimony of Fiords.*—A fiord is a long narrow inlet of the sea which does not terminate abruptly, but is the continuation of an inland glen or valley. It is, in fact, part of a depressed valley which is filled with sea-water instead of being choked up with sand and mud, as in the case of the English valleys. The term fiord is a Norwegian name for such narrow inlets, and is the same as our *firth;* it is the multitude of these firths or fiords which cause the outline of the Scottish and Norwegian coasts to present such a peculiarly irregular and indented appearance. All the larger glens and valleys of western Scotland terminate in fiords, or lochs as they are there called, which are simply the submerged prolongations of the glens; their existence is a proof that the whole country once stood at a higher level than it does now, and that it has not yet been raised again to the level it occupied when the glens and channels were formed. In the same way the fiords of the Norway coast prove that a depression took place before the present rise of the country, and that the land has not yet been re-elevated to the level at which it previously stood, when these ancient valleys were first excavated.

[1] J. Croll, "Trans. Geol. Soc. Edin.," vol. i. p. 330.

5. *Coral Reefs.*—Certain forms of coral reefs are by some geologists regarded as evidence of subsidence. The growth and formation of such reefs will be described in a future chapter (xvi.), and the view that barrier-reefs and atolls can *only* be found in a sinking area will be discussed. Darwin, Dana, Jukes, and other observers have maintained this view, but it is opposed by most recent writers on the subject. Raised coral-reefs are, of course, as undisputable proofs of upheaval as raised beaches are.

General Conclusion.—Combining all the evidence which has been presented to the reader in this and the preceding chapter, we arrive at the conclusion that the earth's crust, instead of being a rigid, immovable mass, as was formerly supposed, is, and always has been, utterly unstable. It is probable, indeed, that no part of the land remains stationary for any long period of time, geologically speaking; but is eventually either slowly depressed, or as slowly upraised to a still higher elevation above the sea. It is certain, at any rate, that the form of the great continents has been continually altered, parts being elevated, and parts depressed, so that every portion has in its turn been brought beneath the level of the sea. It is certain, also, that every country is now dry land only because it has been upraised from beneath the neighbouring sea. This great truth will be still further demonstrated in subsequent chapters.

SECTION II.—Changes produced by the Agencies which operate on the Surface of the Earth's Crust.

IN civilized countries and temperate climates, and especially in regions like our own, where volcanoes are unknown, where no lofty mountain ranges exist, and where all natural phenomena, such as rainfall, rivers, hills, and valleys, are on a comparatively small scale, people are apt to underrate the amount of change which is really taking place all over the surface of the earth, but which is much more apparent and rapid in some regions than in others.

Moreover, those parts of our own country where natural agencies of change are most active are, as a rule, the most thinly populated; men do not congregate on high mountains or on rocky coasts, but build their towns in the lowlands and fertile districts, where perhaps only an occasional flood or storm serves to remind them that the forces of nature are not always gentle and regular in their action.

Lastly, the efforts of the human race are continually directed to the control of these natural forces; ditches are dug to carry off the rain that falls on the land; rivers are embanked and made to keep within definite courses; walls, groynes, and breakwaters are constructed to stop the sea from eating away the coast, and the excessive action of every natural agency is prevented as far as possible.

It is not surprising, therefore, that those who live in a lowland country, and who have never travelled far from the homes in which they were born, should find it difficult to realize the work that may be done, and the results that are actually accomplished, by the uncontrolled forces of nature in other parts of the world. They see around them in old age the same fields, the same slopes, and the same watercourses which they knew when they were children,

and they are apt to think that things had always been as they had always seen them.

In these days, however, people travel very much more than their ancestors did, and many thus become aware that in uncultivated districts, on exposed coasts, on moorlands and mountains, and in regions that are exposed to the extremes of heat or cold, operations are in progress which often cause a large amount of change even within the duration of a human lifetime. In other countries, too, the traveller may view the delta of a large river, he may visit a coral island, he may perchance experience or see the effects of an earthquake shock, or he may find sea-shells of recent species bleaching on slopes that are now several hundred feet above the sea. Still, it does not often fall to the lot of one man to witness all these things, as well as the many other evidences of change that might be mentioned; and many a traveller has returned home without comprehending the part which such changes have played in the economy of nature.

There are, moreover, certain processes of change which the physical conditions of man's existence make it difficult for him to study, even when he specially desires to do so. Those who live by the seaside are familiar with some of the alterations effected by waves and currents on its shores, but they cannot see below the surface of the open sea and watch the drifting of sand into banks, or the slow accumulation of mud and ooze in the deeper water. It requires the dredge and sounding apparatus to give us any information about the deposits which are being formed at the bottom of our seas and lakes. Consequently, as Sir Charles Lyell remarks,[1] "It is not surprising that we estimate very imperfectly the result of operations thus invisible to us; and that when analogous results of former epochs are presented to our inspection, we cannot immediately recognize the analogy. He who has observed the quarrying of stone from a rock, and has seen it shipped for some distant port, and then endeavours to conceive what kind of edifice will be raised with the materials, is in the same predicament as a geologist, who, while he is con-

[1] "Principles of Geology," tenth edition, vol. i. p. 99.

fined to the land, sees the decomposition of rocks and the transport of matter by rivers to the sea, and then endeavours to picture to himself the new strata which nature is building beneath the waters."

In the following chapters we shall endeavour to assist the reader to form some conception of the effects which are produced by these processes of destruction and construction, by bringing to his notice such examples of their action as have been described by experienced observers in various parts of the world.

It is assumed that the student has read some elementary treatise on Physical Geography, and has thereby acquired some knowledge of common atmospheric phenomena, and of the general physical features of the globe. He will then be prepared to follow the more detailed descriptions of the important effects which heat and cold, rain and frost, running water and moving ice, produce upon all surfaces exposed to their action. Some of these agents are chiefly engaged in breaking up and wearing down the rock-masses, others are more concerned in transporting and re-arranging the detritus, but the ultimate result to which all contribute is the re-construction of these materials and their deposition as new formations in the beds of rivers, lakes, and seas.

In considering the operations of these agencies, therefore, it will be desirable to arrange our descriptions in two divisions, confining our attention in the first part to their destructive and dispersive effects, and leaving to the second division the consideration of what may be termed their collective and reconstructive effects.

The processes of disintegration and erosion with which we are to deal in this and the following chapters may be thus classified:—

	Agents.	Action.
I. Terrestrial Agencies.	Atmospheric agents Percolating waters.	Chemical and Mechanical.
II. Fluviatile Agencies.	Rivers . . . . . Glaciers	Chiefly Mechanical.
III. Marine Agencies.	Tides and Waves . Coast-ice	Mechanical.

A. *Processes of Disintegration.*

CHAPTER VI.

I. TERRESTRIAL AGENCIES.

IT is common matter of observation that all rock-surfaces which have been exposed to the action of the weather for any length of time show a tendency to decay and crumble away. The agencies concerned in producing this *weathering*, or disintegration, are several; they act both chemically and mechanically, but they are all so intimately connected in their operations, that any given case of disintegration can generally be shown to be the result of the conjoined action of two or more of them.

They may, however, be arranged as follows, and we shall endeavour, as far as possible, to consider their separate effects.

	Agents.	Mode of action.
Atmospheric.	Rain	Chemical and Mechanical.
	Wind	Mechanical.
	Heat and cold .	Mechanical.
	Frost.	Mechanical.
Underground =	Percolating water	Chemical and Mechanical.

The mechanical effects of these natural agents can be easily understood, but to comprehend their chemical action, the student must have some knowledge of the rudiments of chemical science. These are now so frequently taught in schools, that we assume the reader has a sufficient knowledge of chemical elements and their compounds to understand the explanation of the chemical

action of water; but if he has not this knowledge, he will find a brief notice of such compounds, and of the principal rock-making minerals, in the second part of this book.

Atmospheric Agents.

Rain, and what becomes of it.—All the rain which falls upon the surface of the land is disposed of in one of three ways: 1. Some of it is immediately returned again to the atmosphere by evaporation. 2. Some of it trickles down slopes, and collects into rills and streams, which flow over the surface of the land. 3. Some of it sinks into the ground, and percolates through cracks and joints of the rocks. The rain-water which flows over the surface operates as a mechanical agent, and carries off with it particles of the soil or rock over which it passes in *mechanical suspension.* The rain-water which sinks into the ground acts chemically, it dissolves certain portions of the rocks, through which it percolates, and carries them away in *chemical solution.*

Some of this percolating water is thrown out again to the surface in the form of springs, but the remainder penetrates still further into the substance of the earth, where, with the aid of heat and pressure, it effects great changes in the chemical constitution of the more deeply-seated rocks, and is largely concerned in producing the phenomena of hot springs.

The Chemical Action of Rain.—*Carbonic and Humus Acids.*—Before proceeding to describe the chemical effects of rain-water on the earth, a few words of explanation are necessary, in order that the source of its chemical energy may be properly understood. Pure rain-water would have little effect upon any rock-substance except common salt; its rotting and dissolving powers are mainly due to its capacity for taking up and absorbing certain active agents, viz., carbonic acid (CO_2), the humus acids, and oxygen. Carbonic acid gas exists everywhere in the atmosphere surrounding the earth, though the quantity contained in the air at different places varies considerably. All animals exhale carbonic acid from their respiratory organs, and all

living plants decompose carbonic acid, absorbing the carbon and setting free the oxygen. Dead vegetable matter, by its decomposition and oxidation, gives rise to a set of organic acids, of which the most important are *crenic*, *humic*, and *ulmic* acids, often called collectively the "humus acids." The nature and action of these acids are not yet fully understood, but they are known to have a remarkable power of dissolving many of the mineral substances which occur in rocks. They appear to combine readily with certain metals (such as iron), forming soluble compounds, which are carried away in water and often re-precipitated in other localities. They decompose certain silicates, and will even dissolve silica, the presence of minute quantities of silica in all streams being probably due to their agency.

All these acids, as well as carbonic acid, are readily absorbed or dissolved by water; and, as a matter of fact, all water on the earth's surface contains a greater or less amount of them. Rain takes up carbonic acid from the air through which it falls, and obtains still more, together with humus acids, from the soil through which it percolates. Water thus charged with acids is everywhere soaking into the earth, and it exercises a powerful disintegrating action on the rocks through which it percolates. Some of their constituents are chemically attacked, and carried away in solution; other particles become loosened in the process, and are eventually removed by the mechanical action of the rain-streams.

This gradual decay and disintegration goes on wherever the surface of a rock is kept continually wet with rain and moisture. Plants increase the chemical action by enabling the moisture to lodge and remain for a longer time on the spot, but they retard the mechanical action, and prevent the loosened particles from being carried away, so that these accumulate and form a soil.

The substances soluble in acidified water are:—

More soluble.	Chlorides. Carbonates. Sulphates. Nitrates.	Less soluble.	Most Oxides. Silicates of the alkalies.[1]

[1] The commonest alkalies are sodium and potassium.

The less soluble substances are, however, more soluble in water which has already dissolved alkaline compounds; thus, if rain-water in soaking through rocks near the surface takes up much carbonate of sodium or potassium, it is able to dissolve more of any alkaline silicates it may meet with in its further course through the rocks below. Moreover, if the action of the alkaline solution is aided by that of a high temperature, as is often the case in volcanic districts, large quantities of silica or of silicate may be dissolved in the warm alkaline water.

But, besides these acids, all natural waters contain another active agent in the shape of oxygen gas. This readily combines with metals, and with all oxides which can absorb more oxygen, and by this *oxidation* different mineral compounds are formed. The rusting of an iron nail is a familiar example of this action, and, similarly, any protosalt of iron which may occur in a rock will be oxidized, and a rusty brown colour will generally be imparted to the decomposed and disintegrated mass.

Action of Rain on Calcareous Rocks.—Carbonate of lime enters into the composition of many rocks; some, indeed, such as chalk and other limestones, being almost entirely composed of it. Since the material of such rocks is readily soluble in carbonated water, it is evident that they will show signs of rapid decay and disintegration. A limestone which is nearly pure carbonate of lime, is so completely dissolved that little remains to form a soil, and that little is quickly swept off the surface by rain, so that districts composed of such limestone are often bare and barren, except in the hollows and valleys where soil has accumulated.

Excellent instances of the chemical solution of limestone surfaces occur in certain parts of North Lancashire and Westmoreland. In these counties limestone often forms flat-topped hills and "fells," and where the rock surface is bare of soil it becomes worn and fretted out into a network of open clefts and fissures, a foot or two wide at the top, but gradually narrowing downward to a mere crack or rift at a depth of four or five feet. Protected by the sides of the fissures from the winter winds, and finding foothold in the soil which fills the

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decaying vegetable fibres, it takes up the acids which these evolve, and becomes an active chemical agent for widening and deepening each crevice and cranny.

In some places it is even possible to estimate the actual amount of rock which has been removed in solution since the rock surface has been exposed to the present atmospheric and climatal conditions. Professor Hughes has recently described some cases of "pedestal boulders," which are boulders of some rock foreign to the locality, standing on low flat pedestals of the local limestone; the surface of the pedestals or tables is not like that of the surrounding rock, but is smooth and often striated by the passage of ice (a process which will be explained in a future chapter): we are only now concerned with the fact that the surface of the fell was a smooth one at the time when the boulder came to rest there, and with the further fact that the presence of the boulder has protected a portion of this surface from the wasting action of the rain, while the surrounding parts, to a depth of from twelve to eighteen inches, have been dissolved and carried away. Professor Hughes comments on the influence exercised by vegetation on the mode of weathering, and says: "We see crevices where there can never be any mechanical erosion of the rock opened out into great chasms as lichen, moss, ferns, and grass successively get foothold in it; and round the margin of the great limestone tables on which the boulders rest we see the manner in which the rock is eaten back as the vegetation encroaches along the lines of weakness, furnishing more acid and holding more damp."[1]

The phenomena of the open clefts and chasms are presented on a larger scale on certain limestone plateaux in the Alps, in Bohemia, and in Saxony, which are known as *karren-felder*. The whole surface of these plateaux is worn into a labyrinth of deep and narrow gutters (*karren*), which have been formed mainly by solution, but partly by mechanical erosion; these are often 6 or 8 feet and occasionally from 10 to 20 feet deep.

Limestones which contain an admixture of sand or siliceous matter are converted into the substance known

[1] "Quart. Journ. Geol. Soc." vol. xlii. p. 533.

as *rottenstone*; the calcareous portion being eaten out and carried away in solution, while the insoluble particles are left to form a rotten and friable rock. Impure limestones containing argillaceous (or clayey) matter are similarly disintegrated, the insoluble residue remaining, and crumbling down to form a soil. Such a residual soil, therefore, gives us a rough measure of the amount of rock removed by solution.

By the double process of dissolution and oxidation, calcareous sandstones are often reduced to the condition of a loose brown sand, or friable sandstone. Sands that were originally full of calcareous shells are frequently converted into a ferruginous sand, entirely devoid of organic remains. Thus, in the east of England there are certain shelly sands, called *crag*, the surface beds of which have been so altered by this process that they were long believed to be a distinct formation. The line of separation between the altered and unaltered portions is always clearly defined, but very irregular, because the depth of the former varies much according to local conditions.[1]

The same phenomena have been observed in Belgium, where calcareous sands have been decalcified and oxidized to a large extent, and their true relations to the underlying beds were quite misunderstood until this fact was recognized by M. Vanden Broeck.[2]

The decalcifying action of surface waters is excellently shown in the case of certain sands and gravels which occur in the eastern counties of England, and consist partly of flint sand and partly of small chalk pebbles, and what may be called "chalk sand." Pits dug in these deposits show a sharp contrast of colours and materials; the upper part, beneath the surface soil, to a variable depth, is a brown sandy gravel, from which all the chalk has been dissolved, while the material below is pale yellow, or nearly white, from the quantity of chalk it contains (see fig. 23).

2. *Action on Ferruginous Rocks.*—The humus acids formed by the decay of vegetation, and dissolved in rainwater, play an important part in the dissolution of

[1] See Whitaker, "Quart. Journ. Geol. Soc." vol. xxxiii. p. 122.
[2] See "Geol. Mag." ser. 2, vol. viii. p. 279.

ferruginous minerals, and in the solution, transference, and re-deposition of iron.

Most sands and sandstones are more or less coloured by iron, either in the form of the red ferric oxide, or of the compound green silicate known as *glauconite*, and where such sands form a tract—heath, moor, or high forest-covered ground—through which surface waters can freely percolate, many interesting chemical processes are in action.

In the case of ordinary yellow-tinted sands the crenic acid formed in the surface soil takes up the iron into solution as a ferrous salt, after reducing the peroxide to the protoxide, which forms the base of a crenic salt. Such salts are carried down in solution, and in this way the upper part of the sands is sometimes decolorized, leaving

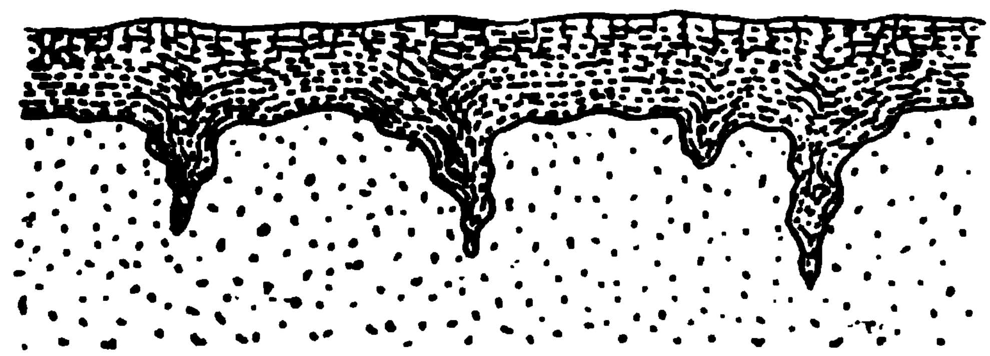

Fig. 23. Decalcification of Sand and Gravel.
a, Unaltered chalky gravel. *b*, Brown sandy gravel.

a white sand, which is prized for glass-making and other purposes. If the percolating water is thrown out as springs, the iron is precipitated by similar chemical action, as the water is oxygenated, in the form of hydrous ferric oxide or limonite, and appears as a scum or soft flocculent deposit on the banks of the issuing stream. In dry seasons, when the water-level is lowered, and the sands are in places completely dried up, air makes its way down at ordinary atmospheric pressure, and the oxygen acts on the ferrous compounds, causing their precipitation, partly as limonite, and partly as basic crenate of iron.[1]

Glauconitic sands are extensively affected by humus acids, the glauconite being decomposed, and converted into limonite, while silica is set free; so that sometimes a great

[1] I am indebted to Dr. A. Irving for the above information.

depth of the sand is changed from a green sand into a yellowish or rusty-brown sand. This result is particularly conspicuous where the country is or has been wooded, as in the case of the large tracts of greensand on the borders of Wilts and Somerset, which was formerly part of Selwood Forest, the decay of the forest litter furnishing the acids. These sands also contain, in some places, lumps of sand cemented by crystalline silica, which may, perhaps, have been formed by re-deposition of the silica set free in the decomposition of the glauconite.

Lastly, volcanic rocks, as basalt, often yield a deep rusty brown soil, the formation of which is doubtless largely due to the action of humus acids on the augite and hornblende they contain, breaking up these silicates, and reducing the iron to limonite. This is especially noticeable in tropical countries, where the growth and decay of vegetation is more rapid, and is probably the chief agency concerned in the production of *laterite*, which will be noticed in another chapter.

3. *Action of Rain on Felspathic Rocks.*—It has been already stated that it is not only the rocks containing *carbonate* of lime which are weathered and worn away by the action of acidified water. Those containing minerals composed of the *silicates* of lime, soda, or potash, yield almost as readily. Granite affords an instance of this, for the felspar which it contains consists of the combined silicates of alumina, potash, and soda. Rain-water falling upon granite decomposes the felspar, removing the silicates of potash and soda, either in the form of a soluble silicate, or by converting them into carbonates, but leaving the silicate of alumina and the other constituents (quartz and mica), which are very insoluble.

By this process the substance of the rock is sometimes so loosened and disintegrated that it can be dug out with a spade. On slopes where the rain-water acts mechanically as well as chemically, the materials of the rock are of course removed as fast as they are loosened, being carried away and deposited elsewhere, partly as clay or kaolin (silicate of alumina) and partly as sand (particles of quartz). The large deposits of kaolin (or china clay) in Cornwall illustrate the enormous destruction of granite

which has there taken place. Orthoclase felspar, which is the variety usually present in granite, is a trisilicate of alumina and potash, with the following normal composition:—

Silica	64·6
Alumina	18·5
Potash	16·9

Kaolin, when quite pure, is regarded as a hydrated bisilicate of alumina, with the theoretical composition of—

Silica	46·6
Alumina	39·5
Water	13·9

Hence we may infer that the compound trisilicate is decomposed by the action of rain-water; that all the potash, and part of the silica is removed in solution; while the alumina and remaining silica have re-united, and taken up water to form a fresh mineral substance. The change may be chemically expressed as follows:—

$$\left.\begin{matrix} Al_2O_3(SiO_2)_3 \\ K_2O(SiO_2)_3 \end{matrix}\right\} + 2H_2O = \left\{\begin{matrix} Al_2O_3(SiO_2)_2 \\ 2H_2O \end{matrix}\right. + K_2O + 4SiO_2.$$

Orthoclase and water = kaolin, potash, and silica.

The extent of the chemical action is, however, better demonstrated in districts where the decomposed granite is not carried away so rapidly, but is left as a loose crumbling mass. A good instance of this is given by Mr. W. Kingsmill in describing the granite of the mountains near Canton in China. He says:—"This granite, wherever it occurs, has been deeply disintegrated, sometimes to a depth of 100 or 200 feet, whilst everywhere, imbedded in the soft, yielding matrix, there occur nodules, of more quartzose character, which have resisted the effects of time and chemical change. The original quartz veins of the granite, broken into small fragments, still traverse the disintegrated mass in all directions."[1]

[1] "Journal of the Geol. Soc. of Dublin," vol. x. p. 2.

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it can be traced, and in which the same fossil shells are found.[1]

Mr. Hudleston did not see his way to accounting for the iron; but Dr. A. Irving believes it to have come in the state of a crenic or humic salt of iron, formed in the overlying soil, and carried down by water percolating through the rock when it was a limestone. A complete reaction then took place: the calcium (as the stronger base) took up the strong acid of the iron-salt, leaving carbonic acid available for union with the iron as ferrous carbonate ($FeCO_3$). But under such conditions this carbonate would not remain; by the alternate access of oxygenated rain-water, and of atmospheric oxygen in dry seasons, it would be slowly broken up, the ferrous oxide being converted into ferric oxide, and the carbonic acid going away in solution. The process is illustrated by the condition of the fossils; shells originally made of carbonate of lime are now converted into limonite.

In a similar manner portions of other limestones have been converted into red hæmatite, or pure anhydrous peroxide of iron, the iron having been derived from the soils left by the red sandstones which once covered them.

Mechanical Effects of Rain.—Everyone is aware that rain exercises a mechanical action in washing off the finer particles of soil, or of chemically disintegrated rock: that all rain falling upon the land and running over its surface carries away a great quantity of such fine material, and that the muddiness of all rills and streams after continuous rain is a clear attestation of this fact. But most people are not fully aware how greatly this action is intensified when the rainfall is very heavy, and when it runs down steep slopes; the effects of a heavy rain-storm in a mountainous district should be witnessed before they can be adequately realized, but it is no exaggeration to say that the rills of rain are capable of moving débris of a size which would constitute gravel. In tropical countries the wearing, excavating, and carrying powers of rain are still greater, in proportion to the much greater volume of water which descends in a given time.

[1] "Proc. Geol. Assoc." vol. xi. p. 122.

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Fig. 25. Earth-pillars in the Valley of the Finsterbach, near Botzen, South Tyrol.

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detrition which has taken place can be actually measured. An excellent illustration of the mechanical effects of rain is furnished by the earth-pillars found in some of the valleys of the Tyrol, and described by Sir Charles Lyell (see fig. 25). These are columns of indurated mud or clay, varying in height from 20 to 100 feet, and usually capped by a single stone or boulder. The history of their formation is as follows. The whole valley was once filled with the hard mud or boulder clay, which is sufficiently solid to stand with a vertical face like a hard rock, and contains numerous and often very large stones or boulders. Through this material a mountain torrent has excavated a deep channel, leaving two platforms, one on each side of its course (P P, in fig. 26). The heat of the sun causes the

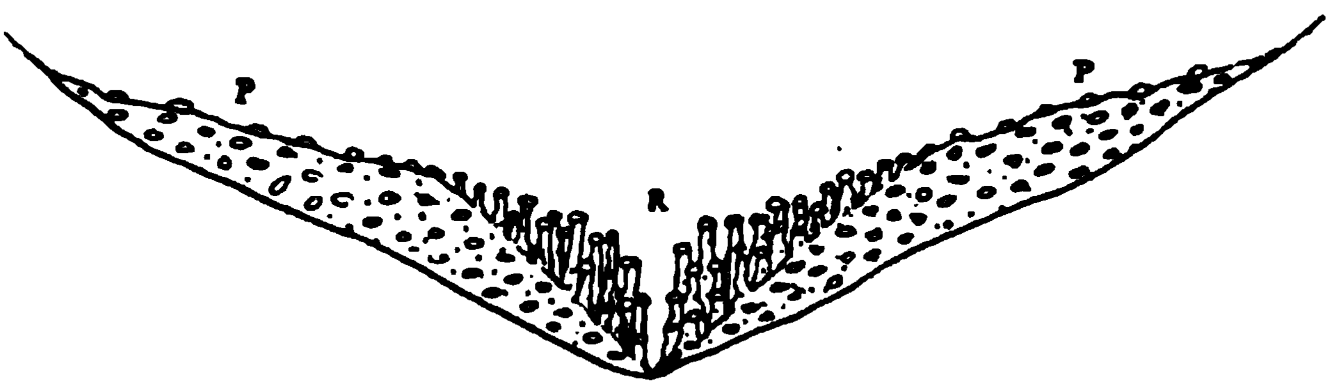

Fig. 26. Section across the Valley of the Finsterbach, to show how the Pillars are formed.

clay to crack in all directions, and these vertical cracks are gradually widened and deepened by the frequent rains which fall in the valley. The rain-drops gather into rills which course down the steep sides of the ravine, and its banks would moulder away like those of other valleys, were it not for the large stones which occur in the clay; these throw off the rain and protect the clay below from its fretting action, while that around is washed away, so that in time detached columns, or pyramidal pillars are left, each capped by the protecting block which was the initial cause of its development. Sometimes the capping-stone falls off, and the column then terminates upward in a point, or becomes separated into several smaller pillars by the weathering out of other blocks within its mass, which in their turn serve as new capping-stones.

The desert country, called "the Bad Lands," in the Washakie Basin, between Utah and Wyoming, U.S., affords another good instance of rapid and extensive erosion by rain. This district is a bare and barren plateau, consisting of soft marls and sands lying in level layers, and terminating towards the south-east in a bold escarpment, which is carved out into numerous blocks, turrets, columns, and citadel-like masses of most peculiar and fantastic forms. The effect is so architectural that from a little distance the scarp-face presents the appearance of a great walled city, with outlying bastions and buttresses. One of the most remarkable of the detached masses is figured in the frontispiece of the first volume of the "United States Exploration of the Fortieth Parallel." This is an isolated column springing from a level desert plain to a height of fully 60 feet; its lower portion forms a kind of base or pedestal 9 or 10 feet high, above which the pillar narrows slightly, and then rises vertically, till it terminates in a roughly-truncated summit. This massive column looks like a monument erected by the hand of man, and its general shape bears no little resemblance to a lighthouse.

In describing these peculiar forms of erosion, Mr. Clarence King, of the U.S. Survey, gives the following explanation of the way in which they have been produced:[1] "The small streams which cut down across the escarpment from the interior of the plateau do the work of cutting the front into detached blocks; but the final forms of these blocks are probably the effect of rain and wind-storms. The material is so excessively fine that, under the influence of trickling water, it cuts down most easily in vertical lines. A semi-detached block becomes quickly carved into spires and domes, which soon crumble down to the level of the plain. Outlying hills or *buttes* are carved away, leaving narrow isolated spires, which finally disappear by the same process of erosion. It seems probable that some of the most interesting forms (like the column above described) are brought out by a slightly harder stratum near the top of the cliffs, which acts in a measure as a protector of the softer materials, and prevents them from taking the

[1] "Exploration of the 40th Parallel," vol. i. p. 399.

mound-forms that occur when the beds are of equal hardness."

Good instances of the manner in which some rocks are wasted away by the action of rain have come under the notice of the writer while surveying a part of Lincolnshire, where the ground consists of a soft, loose sandstone, resting on a bed of stiff clay. The sandstone is easily disintegrated by the action of rain and frost, and its surface weathers into a loose sandy soil, the particles of which are readily carried away by the mechanical action of the rain. The borders of this district form sloping ground, trenched by numerous gullies and valleys, worn by the rills into which the rain collects, and cut down near their terminations to the level of the underlying clay. Some tracts are found where the once continuous sheet of the sandstone has been reduced to the condition of low mounds or hills, separated by wide interspaces, over which nothing but a sandy soil remains to cover the surface of the clay. These interspaces are the sites of the hollows or gullies which were worn in the sandstone, and were gradually deepened and widened by the washing away of the sand, until the surface of the underlying clay was bared. The remnants of the sandstone are thus left as disconnected patches; and these remnants are still being reduced by the wasting action of the rain, and are, as it were, gradually melting away under its influence.

Sometimes a sandstone contains blocks or portions which have been cemented into a hard stone by re-deposited silica; in such cases the blocks are left on the surface of the ground after the removal of the softer portions. Such is the origin of the large siliceous stones known as "Sarsen stones," or *grey wethers* in Berkshire and Wiltshire; these have been derived from certain sands which once covered the chalk in these and other counties, and they now lie scattered on the chalk downs and in the valleys which lie between the hills. In some places they are so numerous as to appear in the distance like a flock of sheep, whence the name of *grey wethers*.

Action of Wind.—Where the soil is dry, and loose enough to be moved by the wind, such particles often operate as powerful agents of detrition. Everyone is fami-

liar with the capacity of wind to blow away particles of dust and sand from the surface of our streets; and the erosive power of a strong blast, charged with particles of sand, is illustrated in the effects of the artificial sand-blast, by means of which patterns are engraved upon glass. Natural sand-blasts produce similar effects upon the rocks with which they come in contact; but the results differ considerably, according as the rocks are of a nature to resist or to yield to such mechanical action.

Very hard rocks, like basalt or compact limestone, when exposed to the continual friction of blowing sand, are pitted and polished in a peculiar manner. On the Fifeshire coast, near Burntisland, for example, blocks of basalt can be seen which have been polished in this manner by the sands of the seashore. The author has also observed polished surfaces on the sides and angles of the limestone rocks, near the great pyramid in Egypt; and the same effect has been produced by wind-blown sand on the surface of many Egyptian monuments.

Where, however, the rocks are soft, or their surface has been disintegrated by the rotting action of rain-water, the results are very different. Such rocks are not polished, but are gradually abraded, and worn away by the friction of the particles driven by the wind. The rapidity of this action depends greatly on the power of the wind, and the size of the particles which it carries; but since the wind cannot raise the larger particles of sand very high above the surface of the ground, it follows that the greatest amount of erosion will take place at, or slightly above, that surface. An isolated block of such a rock as sandstone, if long exposed to sand-drift, will be worn away at the base or undercut, until it presents the appearance of a gigantic mushroom. Some of the celebrated "Brimham rocks," in Yorkshire, exhibit this form very strikingly.

The "tors" and "logging stones," so frequent in granitic districts, probably owe their peculiar form to the combined action of wind and rain. Both granite and sandstone sometimes form piles of rounded or sub-angular blocks, perched one on the other, as if by artificial means; and hence they have sometimes been mistaken for Druidical remains. When examined, however, by the light of geological know-

ledge, it becomes clear that the apparent ruins are the work of Nature's carving tools—wind, rain, and frost. Fig. 27 represents such a pile weathered out of hard sandstone near Lynton in Devonshire.

In arid climates, the agency of sand and dust-storms is greatly intensified; and Sir A. Geikie believes that some of the peculiar features of the sandy plateaus of Wyoming and Utah, previously described, are largely due to the action of wind-driven sand. "Blocks of sandstone or limestone which have fallen from an adjacent cliff are attacked, chiefly at their base, by the stratum of drifting sand, until by degrees they seem to stand on narrow pedestals. As these supports are reduced in diameter, the blocks eventually tumble over, and a new basal erosion leads to a renewal of the same stages of waste."[1]

Action of Heat and Cold.—The mere vicissitudes of heat and cold, without any assistance from freezing water, sometimes exercise important effects, by means of the alternate expansion and contraction which they cause. This is especially noticeable in countries where the daily range of temperature is very great, and is sometimes sufficient to crack and split off pieces of rock. Dr. Livingstone mentions that, in the interior of Africa, he found rocks which had their surfaces so rapidly cooled by radiation at night that the contraction was sufficient to split the stone, and to throw off sharp angular fragments, from a few ounces to one or two hundred pounds in weight. The following are his own words[2]:—

"Several of the mountain sides in this country (Gova) are remarkably steep, and the loose blocks on them sharp and angular, without a trace of weathering. For a time, we considered the angularity of the loose fragments as evidence that the continent was of comparatively recent formation; but we afterwards saw the operation actually going on, by which the boulders are split into these sharp fragments. The rocks are heated by the torrid sun during the day to such an extent that the thermometer placed on them rises to 137° in the sun. These heated surfaces,

[1] Geikie, "Textbook of Geology," p. 320, and Gilbert in Wheeler's "Report of the U. S. G. Surv. W. of 100th Meridian," iii. p 82.
[2] Livingstone's "Zambesi," p. 492.

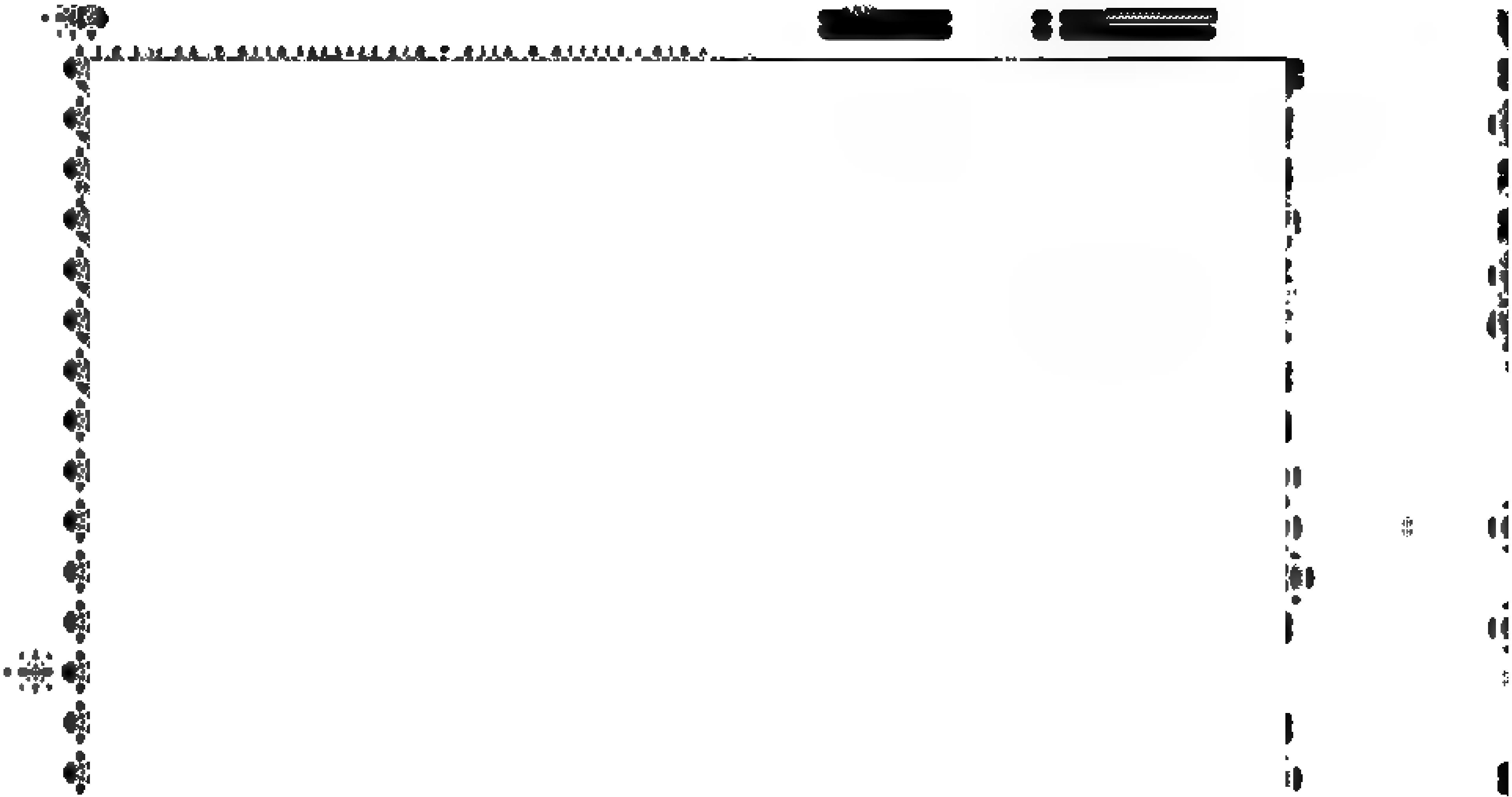

Fig. 27. The "Devil's Cheese Ring," near Lynton, North Devon.

cooling from without in the evening air, contract more externally than within, and the unyielding interior forces off the outer parts to a distance of 1 or 2 feet. Let anyone in a rocky place observe the fragments that have thus been shot off, and he will find in the vicinity pieces from a few ounces to 100 or 200 lbs. weight, which exactly fit the new surface of the original block; and he may hear in the evenings among the hills, where sound travels readily, the ringing echo of the report, which the natives ascribe to the Mebesi, or evil spirits, and the more enlightened to these natural causes."

In warm climates, the continued heat of the summer sun sometimes produces enormous cracks in the earth. In the Sierra Nevada of Southern Spain, where there are districts composed of loose tertiary marls, great fissures have been formed several miles in length, two or three hundred feet deep, and several hundred yards in width. These ravines Professor Ansted describes as having originated in sun-cracks, though they may possibly have been deepened by the winter rains subsequently directed into them.

Great and rapid vicissitudes of temperature, by loosening the component particles of rocks, and causing the formation of cracks, thus facilitate the action of the more powerful agencies of rain and wind.

Action of Frost.—The destructive action exerted by freezing water is due to a peculiar property which it possesses, wherein it differs from most other fluids. Most other bodies contract in bulk as they cool down from a fluid state to the point of solidification; water follows this law of contraction till it reaches the temperature of $39\frac{1}{4}°$ Fahrenheit (4° Cent.) in the downward scale, it then begins to expand, and continues to do so until it becomes solid at the temperature of 32° Fahr. or 0° Cent.

If, therefore, rain or other water soaks into the substance of rocks and fills up the interstices, cracks, and crevices which they contain, and this water then freezes, its conversion into ice is accompanied by an expansion which exercises an irresistible mechanical force and produces important geological results. Not only are the particles of the rock loosened and disintegrated, but the expansion of the freezing water in the larger cracks and fissures, by which

all rocks are traversed, causes the fracture and displacement of large blocks, which are ultimately rent asunder and broken up into smaller pieces.

It is on the sides and summits of mountains, which are subject to great vicissitudes of temperature, that this agency acts with the greatest power and effect. The hardest rocks are broken up by it, and enormous masses are displaced and toppled down precipices, or are set rolling down slopes to suffer still further fracture, and produce still greater ruin in their fall. Its effects may be seen and its amount measured by the piles of angular fragments of all sizes, which are found at the foot of the crags and precipices, and which sometimes form talus- and débris-slopes many hundred feet in height.

Mr. J. F. Campbell thus describes the action of frost in Scotland:—"The silence of the still frosty night is sometimes broken by loud sharp reports followed by the hoarse rumble of stones falling from the mountain peaks. Rainwater sinks into every open chink, and when it freezes the crystal wedge shoves great rocks from their base. The tool-mark is an angular fracture whose shape depends on the nature of the rock which is broken. The finished work is to be seen in high mountains, whose tops are riven peaks, and whose sides lie shivered where they fell." [1]

Captain Beechey in his "Voyage towards the North Pole" describes the amount of this action as very great in Spitzbergen. He found that the mountain sides were undergoing rapid disintegration from the absorption of wet during summer and its expansion by frost in winter. "Masses of rock were in consequence repeatedly detached from the hills, accompanied by a loud report, and falling from a great height were shattered to fragments at the base of the mountain, there to undergo a more active disintegration."

In describing the various erosive agencies now acting upon the slopes and summits of the Rocky Mountains, Mr. Clarence King thus describes the work done by frost and changes of temperature on the summit peaks:[2]—"The whole peak region is seen to be riven with innumerable

[1] "Frost and Fire," vol. ii. p. 181.
[2] "Exploration of the 40th Parallel," vol. i. p. 471.

cracks, which are due to unequal expansion and contraction in a region alternately chilled by radiation and warmed by the sun. Upon the steep slopes and sharp blade-like ridges, the results of such fissuring, together with the leverage of expanding ice, have the effect to dislodge large fragments of rock, and produce immense slopes of débris." He observes that this action takes place at all hours of the day, "but especially when a sudden chill (as during the hour after sunset) has the effect of congealing the percolating waters;" and he adds—"Upon the summits of the Rocky Mountains, the Uinta, and Wahsatch, and at very many points of the ranges near the Pacific coast, I have heard during the day thousands of blocks dislodge themselves and bound down the slopes. The resulting accumulations of débris form a very conspicuous feature throughout the Cordilleras. In many instances they must amount to fully 1,000 feet in thickness. In the Sierra Nevada, where all these phenomena are on a grander scale, I have seen débris-slopes measuring 4,000 feet from top to bottom."

The summits of the Alps present similar appearances, those which are not covered with perpetual snow terminating in jagged peaks and narrow points which are sometimes called *aiguilles* or needles. On these exposed peaks disintegration proceeds at a rapid rate, and showers of stones fall continually night and day, but especially in the afternoon when the sun's rays are hottest and the expanding force is consequently greatest.

The accompanying sketch, fig. 28, representing the forms of some of these peaks, with piles of débris at their bases, is taken, by permission, from Professor Bonney's "Alpine Regions."

General Result of the Destruction of Rocks.—Of all the disintegrating agencies above mentioned, rain is the most important and universal; there are very few districts on the face of the earth which are absolutely rainless, and wherever it falls it operates both chemically and mechanically over large areas at once. There are, therefore, few rock-surfaces in the world which are not affected by this agency, assisted in most cases either by extreme heat or extreme cold, or by both combined.

means uniform; it is most rapid in countries which have a large rainfall, and least appreciable in those which enjoy a dry and equable climate, like that of Egypt. Moreover, it is always greater in mountainous regions than on plains and gentle slopes. Again, as we have seen, some rocks yield much more rapidly than others, and this difference in the rate of waste produces inequalities in the surface, which are especially noticeable where two rocks of very different constitution are brought into conjunction with one another at the surface; one will always be worn down to a lower level than the other.

It should also be remarked that the rapidity with which different rocks yield to the weathering agencies has no relation to their hardness. Where other conditions are equal, soft sandstone resists their action better than the hardest limestone, because the latter yields so readily to the chemical action of carbonated waters, which have no effect upon the former. We have seen, too, that even such hard rocks as granite and gneiss are often decomposed and disintegrated *in situ* to an astonishing depth.

Definition of Terms.—It has been found convenient to employ a general term to express the result accomplished by the combined action of all these agencies, and in most text-books the word *Denudation* is used in this sense, being used to signify the removal of material from the surface of the land. The author has long felt dissatisfied with this use of the term denudation, because it is a perversion of its proper and original meaning. *To denude* (Latin *denudare*), is to uncover or lay bare a surface, and though such denudation necessarily involves the removal of matter, it is not this matter, but the underlying surface which is denuded; consequently it is incorrect to speak of denudation in the sense of wearing away and removing material without reference to the uncovering of any particular stratum. *Degradation* has sometimes been used in this general sense, but it is open to the objection that it has already acquired a different meaning in the English language. *Detrition* (from *detero*, to wear down), has not hitherto been used as a technical term in geology, though the words *detritus* and *detrital* are frequently employed, and *attrition* is a common English word. The word *detrition*, therefore, is not a great

innovation, and in proposing it as a general term to express the result of the processes concerned in producing detritus, and in removing material from the surface of a country, I hope for the support of all geologists who appreciate the value of precise language.

We may then frame the following definitions :—

1. *Detrition* is the removal of rock-material from the land.

2. *Denudation* is the laying bare of rock-surfaces by the detrition of the overlying beds.

3. *Erosion* is the localized action of any detritive agent.

4. *Deposition* is the disposal of the detritus removed from denuded surfaces.

Consequently we shall be correct in speaking of

The detrition of a district.
The erosion of valleys.[1]
The denudation of fresh rock-surfaces.
The transportation and deposition of detritus.

[1] By American geologists the term corrasion is often used for the erosive action of a running stream.

CHAPTER VII.

UNDERGROUND CIRCULATION OF WATER.

A LARGE proportion of the rain-water which falls upon the earth sinks beneath the surface of the soil, and after percolating through the rocks below for a greater or less distance, is thrown out again in the form of springs. The depth to which it sinks depends on the nature of the rocks which it encounters in its downward passage. Some rocks are much more pervious than others; sand and sandstone are pervious by reason of their loose and porous nature; limestone and other hard rocks by reason of the numerous cracks and joints by which they are traversed; while all kinds of clay and shale are comparatively impervious to water, though their constant wetness shows that they are not absolutely impermeable.

Causes of Springs.—The position of springs is therefore always determined by the nature and relative position of the rock-beds, and is generally due to one of the following causes. The underground water is brought again to the surface—

1. By meeting with an impervious stratum.
2. By meeting with a fault or line of displacement.
3. By meeting with some open crack or fissure.
4. By the simple force of hydrostatic pressure.
5. By accumulation in absorbent strata.

1. If rain falls on a pervious rock it descends vertically, but if it reaches a more impervious stratum below, it flows laterally along the top of this bed and breaks out in springs along the line where this comes to the surface of the ground. The strength of the resulting springs will depend

upon the relation between the slope of the ground and the slope of the rock-beds beneath.

Fig. 29 is an imaginary cut or section through a tract of country composed of sand or soft sandstone (*a*, *a*), underlaid by a stratum of clay (*c*, *c*), the surface of which slopes (or dips) slightly towards the east. It is clear that the rain which falls on the western hill will pass down through the sand, and flowing outwards along the surface of the clay will issue in springs along a line on the eastern side of the hill, s^1, being a point on this line.

That there should also be a spring at s^2 on the western side is not at first sight so obvious, since the fall of the beds is towards s^1, and water cannot run up hill: it must be remembered, however, that in passing downwards and outwards through the sandstone, the water will have to overcome a considerable amount of friction, and that this friction will tend to hold the water up under the hill. If, therefore, the rainfall be tolerably constant, the water will be accumulated in the lower portion of the sandstone more quickly than it can escape by the springs, and consequently a certain thickness of the rock will be in a state of constant saturation. The thickness of the saturated portion will decrease towards the sides where the water finds egress, and its upper limit will form a curved line; this is called the *line of saturation*, and when this line rises above the level of the point s^2, the hydrostatic pressure will force the water outwards, and cause a spring at that point as well as at s^1. The former, however, will of course be a weaker spring, and will be the first to fail in a dry season, when the line of saturation under the hill is gradually depressed.

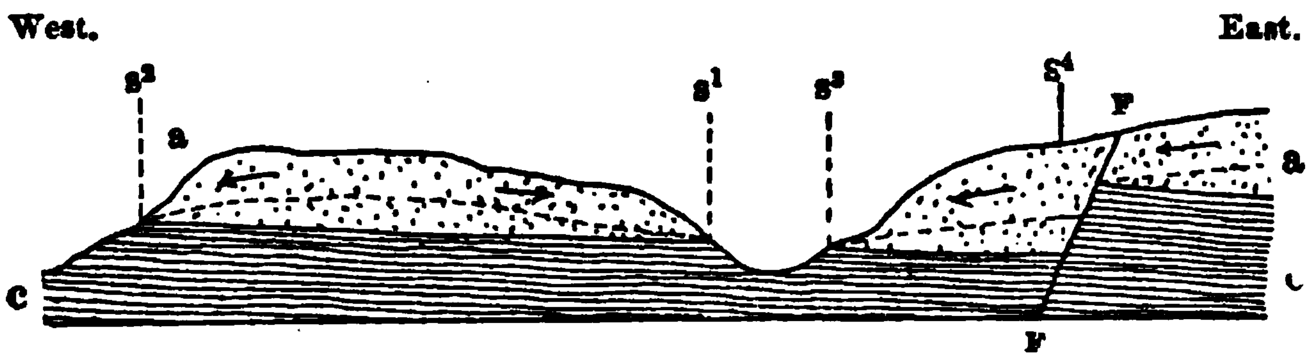

Fig. 29. Origin of Springs.
The line of saturation is indicated by the dotted line.

2. The instance above given is a very simple case, though it is one of frequent occurrence in nature. In other cases, however, strong springs do not occur where they might be expected on the above principle, the regularity of the underground waterflow being interfered with by the existence of open cracks and fissures. It frequently happens that the rocks have been more or less vertically displaced along the plane of such cracks, so that the continuity of the several strata is interrupted. In fig. 29, F F is a line of fault or displacement, on the eastern side of which the rocks are thrown up to a higher level, so that a face of clay is brought against the lower part of the sandstone on the western side. In this case, though there may be springs at the point s^3, yet the main body of water percolating through the sandstone will pass laterally along the line of fracture, and will be thrown out at some point, s^4, along its course where

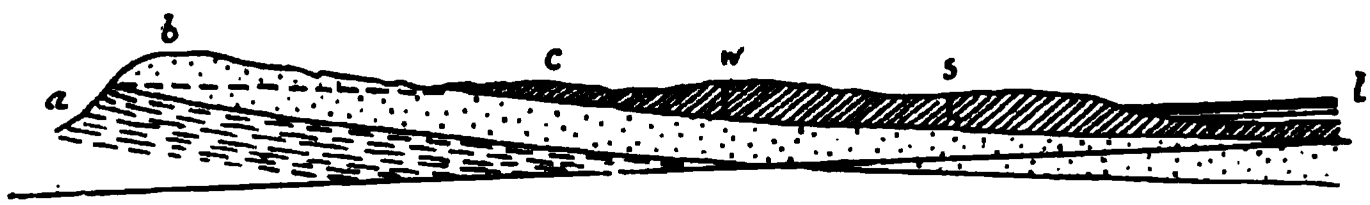

Fig. 30. Diagram to illustrate the conditions of Artesian Wells.

the surface of the ground descends below the level of the saturation line.

3. Artesian wells and springs are due to the confinement of water in an inclined permeable stratum lying between two impermeable strata, the water being prevented from rising to the normal level by the upper impervious stratum, until the pressure forces it up along some line of weakness, or a boring is made down to the water-bearing stratum. Fig. 30 shows the conditions that are necessary for the rise of water in artesian wells; *a* and *c* being impervious strata, and *b* a pervious rock which rises into higher ground than the clay lands on each side. The rain falling on *b* fills the underground extension of that stratum up to the broken line between *a* and *c*. If, then, *c* is pierced by a boring at *w*, the water in *b* will rise to the height of the water-line in that stratum.

Natural artesian springs may be formed through cracks

in the upper stratum when the pressure is great, as in cases where the water-bearing stratum descends below the level of the sea. Such springs occur in the north-east of Lincolnshire, where they are known as "blow-wells." These conditions are shown on the right in fig. 30, where *l* is the sea-level and *s* represents a crack or fissure through which the water rises to the surface.

4. Springs sometimes issue from hill-sides without any obvious cause for the expulsion of the water. If, however, rain-water, after sinking for a short distance into the hill, meets with some horizontal crack or plane of division, it may find it easier to pass along it than to penetrate further downwards. The hydrostatic pressure of the accumulating waters above and behind will force the water along the crack, even if it should slope slightly upwards toward the surface.

5. Springs may also be caused by simple hydrostatic pressure overcoming the force of gravity under the following circumstances. In some districts the rocks are of such a nature that water may slowly descend through them for several thousand feet without meeting with any impervious stratum or great line of fracture. At such great depths, however, the rocks become denser and the cracks and joints much narrower and fewer, so that it may become very difficult for the water to work its way further downwards; it will then accumulate drop by drop, and the pressure of the descending supply will become very great; the water will work its way through lateral cracks and joints, and if it meet with some large fissure or fault opening upwards, it may be easier for it to ascend than to sink further; in other words, the hydrostatic pressure may be sufficient to drive it up to the surface again, where it would issue in powerful and perennial springs. Waters which rise from great depths in this manner generally have a high temperature, like those of Bath, and are known by the name of "thermal springs"; but they must be distinguished from the thermal springs which occur in volcanic districts, and are hot in consequence of the high temperature of the rocks near volcanoes.

6. *Intermittent Springs.*—If a pervious stratum is of small extent, and has no subterranean outlet, the water

which gains access to it will accumulate until it reaches a height from which it can overflow, finding its way to the surface by the nearest outlet. Again, if the channels of ingress are able to supply a greater quantity of water than the ordinary channels of egress can carry off, some other outlet at a higher level will act as a waste-pipe to carry off the superabundant supply and an intermittent spring will be formed.

The nailbournes and winterbournes of the south of England are caused by a gradual rise in the line of saturation under the chalk-hills till the water reaches a level at which there is free egress into some valley or depression ; this, of course, only occurs after periods of great rainfall, and it is only then that these "bournes" begin to flow.

Many dry valleys in chalk districts may be regarded as the

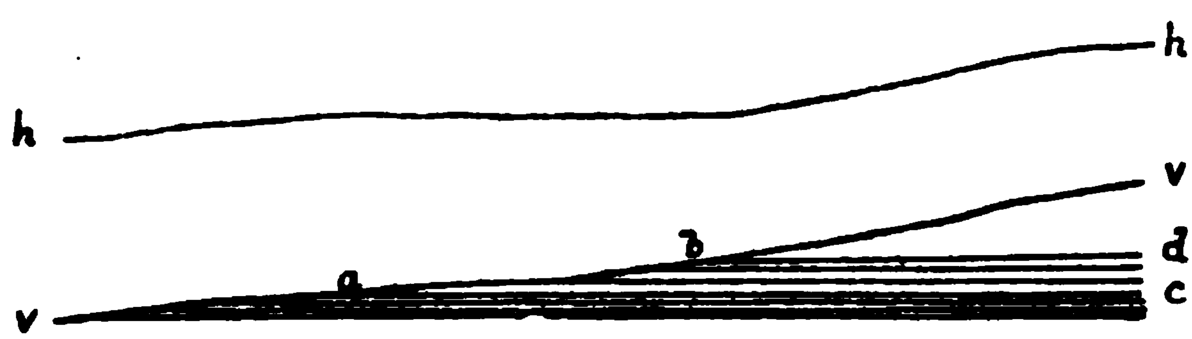

Fig. 31. Diagram to illustrate cause of Winter-bournes.

flood-courses of subterranean streams, that is to say, the bottom of the valley is above the level of saturation in ordinary seasons, and the water makes its way underground through the chalk, but after long-continued rains the level of saturation rises, and the water issues to the surface at some point higher up the valley than the usual spring-head, often indeed at several successively higher points. Fig. 31 represents a vertical section along such a valley, *v v* being the slope of the valley bottom, and the line *a c* indicating the level of saturation in ordinary seasons, so that there is generally a spring at *a*. Suppose however that a wet season raises the general water-level to the height *b d*, this will cause water to issue at successive points between *a* and *b*. The line *h h* is intended to represent the average elevation of the chalk downs above the bottom of the valley.

Such a rise in the water-level can be measured by its rise in deep wells; thus a bourne sometimes issues at a place called the Seven Barrows, near Lambourn in Berkshire, and a well near by then overflows, though in dry seasons it is sometimes dry; this well is 73 feet deep. At other places where bournes issue in Berkshire, Mr. F. J. Bennett has found the rise of the water in wells to be from 70 to 100 feet.

Action of Underground Water.—The waters which sink below the surface and find a passage through the rocks exercise both a chemical and mechanical action.

The power of carbonated water to dissolve certain substances has already been explained (p. 85), and it is evident that this chemical energy will enable the percolating waters to take up any soluble constituents of the rocks through which they pass. The consequences of this solvent power are twofold: not only will the water become charged with many mineral substances in solution, such as the carbonates of lime, iron, and magnesia; but the pores, spaces, and cracks within the rocks will be widened and enlarged by the removal of these materials. The results of this chemical action are most conspicuous among calcareous rocks, through which long underground caves and passages have been excavated by the flow of subterranean waters.

As a mechanical agent, underground water acts partly as a lubricator, and partly by removing small particles of the rock in suspension, either because they have previously been loosened by its chemical influence, or because the rock is of a loose and incoherent nature like sand. The results of this action are most evident along cliffs and slopes, especially where conditions are favourable to the formation of springs. Cracks are widened and particles are removed till the cohesion of large masses is so weakened that they fall or founder down to lower levels. Such disruptions are called landslips.

Chemical Effects:—*Matter removed in Solution.*—The materials abstracted from the rocks through which water has percolated are, of course, found in solution when the water issues to the surface again in the form of a spring. All well and spring waters contain a certain amount of mineral matter, and this is held in solution until the water

is exposed to evaporation in the air. The quantity of such mineral matter varies greatly; in ordinary springs of drinkable water rising from calcareous rocks there is, on the average, about 30 parts per 100,000, or 21 grains in a gallon of water, but sometimes there is as much as 90 parts (or 63 grains) in a gallon. Springs which contain a larger quantity of such matter in solution are generally called mineral springs, and they often taste sensibly of some of the saline ingredients; in these the amount varies from 100 to 3,000 parts per 100,000, *i.e.*, from 70 to 2,100 grains per gallon.

The substances most commonly found in spring-waters are:—

Carbonate of lime ,, magnesia	making temporary hard water.
,, iron	making chalybeate water.
Sulphate of lime ,, magnesia	making permanent hard water.
Chloride of sodium ,, magnesium	making saline water.
Carbonate of soda Sulphate of soda	making alkaline water.

Waters which rise from great depths, or which traverse heated rocks in volcanic districts, acquire a high temperature, and are then able to dissolve silica and other less soluble matters; moreover, the presence of alkaline carbonates (*i.e.*, those of Soda and Potash) facilitates the solution of silica, and enables the water to hold a larger quantity of it in solution. Springs of warm water are often called *thermal* springs.

The amount of material thus abstracted from the rocks and carried away in solution is very great, as will appear from simple calculations based on the analyses of the waters of various springs. Two instances will suffice: (1) Bischoff says that there are fifty springs near Carlsbad, giving out 800,000 cubic feet of water in twenty-four hours, from which a mass of stone weighing 200,000 lbs. could be deposited in that time. Carlsbad itself is built upon a mass of peculiar calcareous rock deposited by these springs, and known locally by the name of Strudelstein

the whole valley is, in fact, filled up with similar deposits. (2) The Bath wells yield 181,440 gallons a day, and each gallon contains from 144 to 168 grains of mineral matter in solution; the smaller amount is equal to 3,732 lbs. per day, or 608 tons in a year. From these figures Professor Ramsay has calculated that if the mineral contents could be precipitated and solidified into a rock like limestone, the amount annually discharged would form a column 3 feet square and about 912 feet high. The following are the ingredients of the Bath water according to Professor J. Attfield:—

	Grains per gallon.
Carbonate of lime	7·84
Sulphate of lime	94·10
Nitrate of lime	·56
Carbonate of magnesia	·56
Chloride of magnesium	15·24
Chloride of sodium	15·15
Sulphate of soda	23·14
Sulphate of potash	6·70
Nitrate of potash	1·05
Carbonate of iron	1·21
Silica	2·70
	168·25

Formation of Holes, Pipes, and Caverns.—The dissolving action of rain-water is also made apparent by the holes and hollows which occur in the surface of all limestone districts; any little depression where water can lodge is made deeper, the joints in the rock below are widened, and a funnel-shaped cavity or *swallow hole* is the ultimate result.

If the surface is covered by any kind of soil, with a growth of trees and plants which push their roots down to and into the rock, the rain-water is continually guided by these roots to certain points. The rock is consequently dissolved more rapidly below these points, and a hollow or pipe is gradually formed, into which the overlying soil sinks. Long chimney-like holes are sometimes produced in this way, filled with materials derived from the surface soil and descending for a long distance downward through the rock. Small pipes and pockets may be seen in many chalk-pits, varying in depth from a few feet to many yards, and generally filled with gravel, sand, or loam derived

from the overlying soil. Excellent instances are visible in the chalk quarries by the side of the Great Northern Railway at Hitchin. Several huge funnel-shaped pipes, filled with gravel, are here seen descending vertically into the chalk, and passing down below the level of the railway.

These pits or pipes are still in process of formation. Dr. Darwin says:[1] "During the last forty years I have seen or heard of five cases, in which a circular space, several feet in diameter, suddenly fell in, leaving on the field an open hole with perpendicular sides, some feet in depth. This occurred in one of my own fields whilst it was being rolled, and the hinder-quarters of the shaft-horse fell in; two or three cartloads of rubbish were required to fill up the hole. . . . The rain-water over this whole district sinks perpendicularly into the ground, but the chalk is more porous in certain places than in others. Thus the drainage from the overlying clay is directed to certain points, where a greater amount of calcareous matter is dissolved than elsewhere."

In districts where there is little or no soil, the *swallets* or pot-holes remain open, and are often wide and deep cavities into which the surface waters run and disappear. Such holes are common in the limestone districts of Yorkshire, and an account of them has been published by Mr. L. C. Miall, who mentions Thund Pot and Hellen Pot as among the largest.[2]

There would appear to be two modes in which such swallow holes can originate. Some are due to direct solution from surface waters, and occur singly or in scattered groups; others occur in linear groups, and are due to unequal subsidence over a line of fissure. The latter are chiefly found where the limestone has a covering of shale, clay, or peat; the fissures below are then widened by aqueous solution, till the roof can no longer support itself at certain points, but falls in and pits the surface; the result is a succession of swallow holes, in which streams are often engulphed.

Mr. Whitaker remarks that in Berkshire there are always swallow holes at or near the junction of the chalk and ter-

[1] "Vegetable Mould and Earth Worms," p. 137.
[2] "Geol. Mag.," 1870, Ser. 1, vol. vii. p. 513.

tiary beds, and that the small streams flowing off the latter often run into them; sometimes disappearing into a funnel-shaped hollow, sometimes flowing into a small pool, the level of which never alters, notwithstanding the continual flow of water.[1]

In other countries swallow holes occur on a still larger scale. Dr. Emil Holub describes a thick limestone formation as extending over hundreds of square miles in the Transvaal and Griqualand West (South Africa), and notices the frequent occurrence over this tract of funnel-shaped chasms, sometimes as much as 200 or 300 yards in circumference, and from 25 to 40 feet in depth. "At first sight," he says, "they have the appearance of being circular, but on investigation they nearly always prove triangular or quadrilateral. The interstices of broken rock with which their inner surface is lined are filled up by the surrounding earth, which thus forms a luxuriant bed for the roots of trees and shrubs, which tower up above, and become conspicuous upon the generally barren plain." From the bottom of these funnels fissures and underground passages radiate in different directions, and Dr. Holub describes his descent into one which bears the name of Wonderfontein. From others the water does not appear to escape so readily, and consequently the funnels form small lakes or pools of clear water.[2]

Subterranean Channels and Caverns.—The underground waters are often gathered into streams of considerable size, and surface rivers are sometimes engulphed in rifts or caverns, and flow for long distances in subterranean channels before they again emerge to the surface.

Such is the stream which traverses the great caverns of the Peak in Derbyshire.

In Staffordshire the river Manifold gradually dwindles away in its limestone bed till the water finally disappears in a fissure near Grindon, and after flowing underground for a distance of three miles, reappears near Ilam.

In Yorkshire, the river Aire issues from Malham Tarn,

[1] See also J. Prestwich, "On some Swallow Holes near Canterbury," "Quart. Journ. Geol. Soc." vol. x. p. 222.

[2] "Seven Years in South Africa," by Dr. Emil Holub, vol. i. p. 170.

a circular lake about a mile in diameter, on the summit of a lofty moor, and after flowing a short distance it descends into a subterranean channel, whence it issues again at the foot of Malham Cove, a perpendicular limestone rock 288 feet high.[1]

Sometimes, when the courses of such rivers are not far below the surface of the ground, a portion of the roof falls in, and leaves a deep trench, at the bottom of which the brawling waters of the stream may be distinguished among the masses of fallen rock. Good instances of this kind occur in the courses of the streams which flow beneath the great limestone plains of central Ireland, and have been thus described by Mr. Jukes:[2] "Sometimes the roof of one of the subterranean river-courses has fallen in for some distance, so as to form a narrow rocky valley, from a hundred yards to a mile or two in length. The river comes from under the limestone mass at one end, and runs below it at the other, the rock at either extremity of the fallen-in valley rising like a wall along the face of some strong joint. In the country, above and below one of these excavations, no one would have any suspicion of the course, or even of the existence of the subterranean river."

Instructive examples occur also in Greece. "It appears that in the more elevated districts of the Morea there are many deep land-locked valleys or basins, closed round on all sides by mountains of fissured and cavernous limestone. When the torrents descending from the surrounding heights are swollen by the rains, they rush into the enclosed basins; but instead of giving rise to lakes, they are received into gulfs or chasms, called by the Greeks *Katavothra*, which correspond to what are termed swallow holes in the North of England."[3] In summer it is possible to penetrate far into these chasms, and within is found a suite of chambers communicating with each other by narrow passages. The outlets are usually near the sea-shores of the Morea, but are sometimes situate beneath the sea.

To the solvent action of such streams then, aided doubt-

[1] Conybeare and Phillips, "Geology of England," p. 397, note.
[2] "Manual of Geology," third edition, p. 458.
[3] M. Boblaye, in Lyell's "Principles of Geology," tenth edition, vol. ii. p. 516.

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180 yards from the entrance, is 300 feet long, and about 100 feet high, and is adorned with translucent stalactites of fantastic forms. The river is believed to continue its subterranean course for about eight miles.

The cavern of the Peak, in Derbyshire, is 2,250 feet in length, and consists of a succession of narrow passages and lofty chambers, some of the latter being 200 feet broad, and more than 100 feet high. Clapham Cave, which runs a long distance beneath Ingleborough, in West Yorkshire, is another remarkable instance.

The Mammoth Cave, in Kentucky, U.S., is well known. This has many branches extending in different directions, and one of them has been followed for a distance of ten miles without reaching its termination. Like other caverns, it is a system of large cavities connected by narrow tunnels; one of the chambers occupies an area of no less than ten acres, and has a height of 150 feet in some places.

It is not only in ancient limestones that such caverns occur; they abound in the limestone rocks of elevated coral islands, where the excavation of such cavities must have been comparatively rapid. The Rev. J. Williams states that in the island of Atiu, one of the Sandwich Islands, there are seven or eight of large extent. He entered one, and wandered a mile along one of its branches, without finding an end to its "interminable wanderings."[1]

The island of Barbados in the West Indies affords a curious case of a subterranean system of drainage. This is a raised coral island, and six-sevenths of it are covered with coral-rock, which varies in thickness, but is often from 150 to 200 feet thick. On this area there are no permanent surface streams, all the rain falling on it sinks into the limestone rock, and is carried off by underground channels, most of which open into the sea by submarine outlets, whence fresh-water springs issue into the sea. The coral rock seems to be traversed by a veritable network of channels and caverns; some of these are dry, and can be explored for long distances; others are still occupied by the streams which made them, and they exhibit the usual features of limestone caverns.

[1] See Dana's "Coral Reefs," p. 361.

Mechanical Effects:—*Landslips.*—Any slope of clay or shale has a tendency to slip after heavy rain, as may be seen in many of our railway cuttings. In dry weather the contraction of the clay leads to the formation of internal cracks, and when rain falls the water flows down these, removes particles from their sides, and so lubricates the contiguous surfaces that portions slip and founder down by their own weight. The foundering of clay slopes can be well studied in the Isle of Sheppey, where large portions of ground slip seaward every winter. The manner in which these slips are produced has been thus described:[1]— "In the hot weather the surface of the ground is cracked from the shrinking of the clay, and the cracks are seen as gaping fissures about six inches across and many yards in length and depth. When the rain falls, it find its way into these cracks and softens the clay at the bottom. If the crack is near the cliff, the half detached mass being now heavier, owing to the addition of the water, while the cohesion of the attached portion is lessened, slips down to the shore below, sometimes almost unbroken, sometimes breaking off by parallel cracks into a series of terraces, or even in part creeping down among the fallen stiffer masses as a glacier-like mud-flow. The sea washes this débris away from the base of the cliff, and the process is repeated."

In harder rocks the open cracks and joints afford access to the rain-water, and frost often assists in the process.

Professor Heim has recently called attention to the importance of these massive landslips (*Bergstürze*) in mountainous regions; and the Rev. A. Irving has dwelt upon the part which they play in the formation of many lakes.[2]

Three principal types of such landslips may be recognized in Switzerland:—

1. Cases in which thick accumulations of débris upon mountain sides become saturated with water after heavy rains. The water, by increasing the weight of the mass, and diminishing the friction, causes the whole to slide

[1] Professor Hughes, in Whitaker's "Geology of the London Basin," Mem. Geol. Survey, vol. iv. p. 387.
[2] "Geol. Mag." Dec. 2, vol. x. p. 160.

down the slope. "One of the most remarkable instances of this class is the movement which is now going on at the village of Fetan, in Unter Engadin. Houses are tilted, or parted asunder; and the solid rock on which the tower of the church stands is found to be but a great [detached] mass of granite, which is slowly moving with the looser materials in which it lies embedded."[1]

2. Cases in which the strata forming a mountain slope towards a valley on one side of it, so that portions become loosened by the action of rain and frost, and slip bodily down into the valley below. The falls from the Rossberg near Lake Zug belong to this type. In 1806 large slices broke away from the side of this mountain, and fell into the valley of Goldau, burying villages, and causing great destruction and loss of life. The great landslip at Elm in 1881 is another well-known case where a portion of the Tschingel Alp gave way and fell on to the village of Elm 2,000 feet below, crushing the greater part of it. The amount of fallen rock was estimated by Professor Heim at ten million cubic metres, and each cubic metre of the slate and shale which fell would weigh about two tons.

3. Cases in which huge masses of rock are detached from the higher slopes, and form avalanches of rock and earth, which descend into the valleys. Such falls frequently destroy whole villages, and sometimes lead to the formation of lakes, either permanent or temporary; and the bursting of the latter causes destructive floods below the site of the barrier. Thus, in 1512, a mass fell from Monte Crenone, above Biasca, destroying 400 houses, and killing 600 people. "The river Blegno was dammed up by it, and formed a lake, which remained for three years, when the barrier was broken through, and the whole valley, down to Lake Maggiore, devastated by floods." In 1618, the village of Plurs, in Bergell, was totally overwhelmed, and still remains completely buried.

"No Alpine valley," says Professor Heim, "is without such heaps of débris and traditions having reference to them. A still older series belongs to a time extending far back beyond the range even of tradition." He particularly

[1] Heim, quoted by Irving, *op. cit.* p. 161.

describes an enormous fall near Flims, which is 2,000 feet high, and appears to have taken place at a time anterior to the glacial epoch.

The recent landslip in the valley of the Rhone (January, 1883) is another instance. Between Bellegarde and Evian, the Rhone runs through a narrow rocky gorge, bounded on one side by a lofty spur of the Jura, and on the other by the precipice of Mont Vuache, along a ledge of which the railway is here carried. From this mountain, an enormous mass of earth and rock fell, destroying a short tunnel on the railway, and stretching across to the other side of the valley, so as completely to block the course of the Rhone. The waters immediately began to gather behind the barrier; and had it been strong enough to dam them back for a long time, the consequences would have been tremendous, but fortunately the river soon forced a passage through the mass of débris.

In the British Isles, landslips are most frequent where the superposition of pervious upon impervious rocks cause the issue of springs along the foot of a slope or cliff. In such cases, the water is perpetually sapping the foundations of the upper beds, and lubricating the surface of the impervious stratum below, till large masses founder down at once, and form a series of confused mounds and terraces.

The well-known Undercliff of the Isle of Wight is an example of this, being in reality a succession of landslips, caused by the slipping of masses of chalk and greensand over the surface of the dark blue clay which underlies them. This clay is locally termed "the blue slipper," but is known to geologists under the name of *gault*. The fallen masses form a series of irregular terraces between the real cliff and the shore, and extend for a distance of six miles along the coast. This undercliff and its formation is indicated in fig. 33, which is a diagrammatic section from north to south (from Mantell's "Excursions in the Isle of Wight").

The history of a single landslip, such as that of the great Axmouth slip, which occurred in 1839, will be instructive. The arrangement of the beds on this coast is similar to that in the Isle of Wight—beds of chalk and greensand

resting on a retentive stratum of clay, the surface of which has a slight slope seaward. The following account is abridged from Sir Charles Lyell's description:[1]—"In 1839, an excessively wet season had saturated all the rocks with moisture, so as to increase the weight of the incumbent mass from which the support had already been withdrawn by the action of springs. Winter came on, and frost exercised its usual expansive effects on the water in all the vertical cracks and fissures, and naturally tended to force the masses outwards and seawards, while their slippery basis of watery sand decreased the friction, and rendered their descent over the surface of the clay a comparatively easy process. These causes gave rise to a convulsion, which began, on the morning of the 24th of December, with a

Fig. 33. The Undercliff, Isle of Wight.

crashing noise. On the evening of the same day, fissures were seen opening in the ground, and the walls of tenements rending and sinking, until a deep chasm or ravine was formed, extending nearly three-quarters of a mile in length, with a depth of from 100 to 150 feet, and a breadth exceeding 240 feet. The tract intervening between this fissure and the sea, including the ancient undercliff, was carried bodily forward, and the pressure of this enormous mass forced up the shore in front of it, producing a long, upraised ridge, covered with large blocks of rock, which, at the time of the occurrence, were invested with seaweed and corallines, and scattered over with shells and star-fish.

"Far larger instances of ancient landslips, of which no record is known, and which took place, perhaps, before

[1] "Principles of Geology," tenth edition, vol. i. p. 536.

historic times, or even before the country was inhabited by man, may be observed in some parts of the south-west coast of Ireland. On the coast west of Bearhaven, in county Cork, and west of Brandon Head, in county Kerry, as also in Derrymore Glen, between the mountains called Baurtregaum and Cahirconrea, there are great cliffs, where the rocks are thrown into positions which appeared puzzling and abnormal, until it was ascertained that they formed parts of gigantic landslips. Masses of land, with cliffs 800 feet high, were then seen to be nothing but a confused heap of broken ruins, their cracks and dislocations being superficial only, and not extending below the level of the sea."[1]

[1] Jukes' "Manual of Geology," second edition, p. 102.

CHAPTER VIII.

FLUVIATILE AGENCIES.

1.—*Action of Rivers.*

HOW a River is formed.—A river results from the union of streams, just as one of these streams results from the union of minor streams or brooks. The feeders of a stream or river are called its tributaries; the area which is drained by the whole number of these tributaries is called the *area of drainage*, and a river with its tributaries is often spoken of as a *system of drainage*. The sources of supply are the rain which runs off the ground within the drainage area, and the springs which rise to the surface within that area. Where a river has its sources in mountains that are permanently snow-clad, the melting snow becomes a source of supply in summer. The ridge or line of country from which the rainfall runs off in different directions is called a *watershed*, or *water-parting*.

Laws of Flow.—The rate at which water flows from a range of hills to the sea varies greatly in different parts of its journey, because the slope of the watercourse differs in different places. The velocity of a stream at any one place depends primarily on the inclination of the channel at that place, and secondarily on the volume of water passing through it.

The inclination of the channel varies from a steep slope, forming rapids, to a nearly level plain, through which the water is only propelled by the force of the stream behind it. The channel of a mountain torrent often has a slope of over 200 feet per mile; thus the Reuss, between Audermatt and Amsteg, has a fall of about 212 feet per mile. As examples of the channel slopes lower down the valley of a

mountain river we may take the case of the Inn between St. Moritz and Jenbach. Between St. Moritz and Samaden (3 miles) the average slope is 65·3 feet per mile, between Samaden and Landeck (80 miles) it is about 39·3 feet per mile, from Landeck to Innsbruck (53 miles) it averages 13·8 feet, and from Innsbruck to Jenbach (23 miles) about 4 feet per mile.[1] When a river reaches great plains that are not far above the sea-level its slope is often only a few inches per mile.

Again, the velocity of a current varies with the volume of the streams. If two streams have the same slope for a given distance, but there is more water in the one than in the other, the larger stream will have the greater velocity. Also if a stream is in flood its velocity at a given spot is greater than when there is only the usual volume of water.

Further, not only does the velocity of a river vary at different times and in different parts of its course, but it also varies in different parts of the same cross-section of the current, on account of the friction between the flowing water and the river-bed. Thus the middle of the surface of the stream flows faster than the sides, and the water at the bottom travels slowest, the velocity of the bottom water being often only half that of the surface water in mid-stream.

With regard to the actual velocities of streams, it appears that, except in falls and rapids, the fastest currents do not exceed 20 miles an hour, and a current of 8 or 10 miles an hour at the surface is a rapid stream, capable of moving large pebbles. It is stated that the average speed of an ordinary river-current varies from 6 miles an hour when the stream is high and swollen, to about 1¼ mile an hour when the water is low. The Ohio river at Cincinnati, where its fall is 4 inches to the mile, has a mean surface speed of 1⅛ mile an hour when the water is low (*i.e.*, 6 feet deep), when the water is high (54 feet deep) the average current is nearly 6 miles an hour, the actual rate in the middle being 6·35 miles, and at points half way toward either bank 5·85 miles per hour.[2]

[1] Prof. T. G. Bonney, "Geol. Mag." Dec. 3, vol. v. p. 54.
[2] Hinman's "Eclectic Physical Geography," 1889, p. 213.

Transport of Detritus.—Everyone knows that a mountain torrent rolls pebbles along its bed, and that a river in flood is turbid with the mud which it carries; but the geologist requires some more definite information on this important subject. In studying the power of running water to transport rock-material from higher to lower levels there are three primary facts to be remembered:—

1. *Loss of Weight.*—All earths and stones lose one-third of their weight when suspended in water, consequently the force required for lifting them is only two-thirds of the force necessary to lift them through air; and still less force is required to push or roll stones along the bed of a stream.

2. *Shape of the Fragments.*—Rounded pebbles can be rolled along by a current of water which would be quite unable to move flat slabs of the same weight; conversely, flat slabs or flakes would sink more slowly than rounded fragments of the same cubic contents. Flakes of mica might therefore be transported onwards where grains of quartz would sink, though the latter might be lighter than the former.

3. *Velocity of Current.*—As already mentioned (p. 126), the velocity of a stream depends upon the volume of water and the declivity of the channel. An increase in either of these factors quickens the current, and increased velocity means increased power to transport material. Mr. A. Tylor made experiments from which he arrived at the conclusion that the velocity increases as the cube root of the increase of volume on the same slope, and as the cube root of the increase of slope if that is increased and the volume of water is unaltered.[1] We learn from Mr. W. Hopkins that the transportive power of water increases as the sixth power of the velocity of the current. Thus if the velocity is doubled its motive power is increased 64 times; if its velocity is trebled, its motive power is increased 729 times, and so on.[2]

From Mr. Hopkins' law above quoted we can express the transportive power of streams in terms of the weight

[1] See "Geol. Mag." Dec. 2, vol. ii. p. 446.
[2] "Quart. Journ. Geol. Soc." vol. iv. p. 92.

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fragments of rock which have fallen from the neighbouring crags into the water-course. These blocks, arresting the force of the stream, are worn and fretted by the particles of sand and mud with which the water is charged, till they become smooth and rounded by the constant attrition. Some greater flood than usual then sets them in motion, they are knocked and ground against one another till they are broken up and converted into a number of smaller stones or pebbles. These are rolled onward into the brook, where they undergo a continuation of the same mechanical operation, being perpetually ground into smaller and smaller fragments, till they eventually become grains of sand and particles of mud. In this shape they are delivered into the river, and after many detentions by the way, are ultimately swept into the sea.

In a clear and shallow stream flowing over a sandy bed the manner in which sand and small pebbles are rolled along the bottom can often be watched. The bed generally exhibits a number of transverse ridges or ripples, each with a gentle slope along the up-stream side, and a steep slope on the down-stream side. The particles of sand are rolled by the current up the gentle slope till they come to the crest of the ridge, when they drop down the steep slope into the furrow. There they are covered up by succeeding particles, the front of the ridge being continually advanced as the particles from behind are pushed over it.

M. du Buat, in his work on Hydraulics, gives a table which shows the velocity required to move detritus of various sizes; and this in a little clearer form for pebbles of average rock, and extended by Professor Bonney, is given below:—

	Velocity of current.			Size of material moved.
One of	3 inches	per sec.	moves	fine clay or silt.
„	6 „	„	„	fine sand.
„	8 „	„	„	particles the size of peas.
„	1 foot	„	„	pebbles as large as beans ($\frac{1}{2}$in.)
„	2 feet	„	„	pebbles of 1 inch diameter.
„	2·82 feet	„	„	pebbles of 2 inches diameter.
„	3·46 „	„	„	pebbles of 3 inches diameter.
„	4·00 „	„	„	pebbles of 4 inches diameter.

Velocity of current.				Size of material moved.
One of 4·47	feet per sec.	moves		pebbles of 5 inches diameter.
„ 4·90	„	„	„	pebbles of 6 inches diameter.
„ 5·29	„	„	„	pebbles of 7 inches diameter.
„ 5·65	„	„	„	pebbles of 8 inches diameter.
„ 6·00	„	„	„	pebbles of 9 inches diameter.

A current of 6 feet per second is about 4 miles an hour, but this is the velocity at the bottom, which is about half that of the surface in the middle. To move pebbles of 4 inches diameter requires a current of $2\frac{3}{4}$ miles an hour—that is, a central surface velocity of $5\frac{1}{2}$ miles an hour.

Matter in Solution.—Besides the detritus which is mechanically transported by the force of the current, the waters of every river contain a large amount of material in chemical solution. The mineral substances which occur in spring-water have already been mentioned, and these, of course, will be present in the rivers that are fed by springs, though in smaller proportions, because of the admixture of rain-water, by which, however, some other ingredients are introduced. The following is a list of the substances generally or frequently found in river-waters:—

Carbonates of lime, magnesia, and soda.
Sulphates of lime, magnesia, potash, and soda.
Chlorides of calcium, magnesium, and sodium.
Silicates of potash and soda.
Peroxides of iron and manganese.
Silica and alumina in small quantities.

The amount of mineral matter dissolved in the water of brooks and rivers varies from 15 to 50 parts in the 100,000 parts of water. The water flowing off siliceous rocks seldom has more than 20 parts, while that running off calcareous rocks generally contains over 30 parts per 100,000. The amount in ordinary river-water may be taken as about 20 parts per 100,000, but it varies with the rainfall, being at a maximum when the rainfall is least and the supply of water is in consequence mainly derived from springs, and it is at a minimum after times of heavy rainfall.

The Thames carries past Kingston 27 parts per 100,000, or 19 grains of solid matter per gallon of water, and the

mean annual discharge of water at the same place is at the rate of 1,250 millions of gallons a day. From these data Professor Prestwich has calculated that the average amount of dissolved mineral matter carried by the Thames past Kingston every 24 hours is 1,502 tons, which is equal to 548,230 tons in the year. Of this quantity about two-thirds (say 1,000 tons daily) is carbonate of lime, and 238 tons is sulphate of lime, while smaller proportions of magnesium carbonate, sodium and potassium chlorides, sodium and potassium sulphates, silica, and a little iron and alumina, constitute the remainder.

Mr. Mellard Reade has calculated, from the data given in the Sixth Report of the Rivers Pollution Committee, that all the rivers of England and Wales taken together remove in solution 143·5 tons of mineral matter from every square mile per annum, or a total amount of 8,370,630 tons per annum. This at 15 cubic feet to a ton gives 125,559,450 feet, and this is equivalent to a general lowering of the surface by ·0077 of a foot, or nearly one-tenth of an inch in a century. Taking the world generally, Mr. Reade computes that the quantity of mineral matter carried off the surface of the land by rivers is about 100 tons per square mile per annum, and that of this about 50 tons may be carbonate of lime.[1]

In European rivers carbonate of lime generally forms more than half the total amount of matter in solution; its mean quantity, according to Bischof, being 11·34 in the 100,000. The waters of the Rhone appear to remove a larger amount of carbonate of lime from each square mile of drainage basin than any other European river. The total solids in solution amount, according to Mellard Reade, to 232 tons per square mile per annum, and, according to Bischof's analysis, about two-thirds of this must be carbonate of lime.

After the carbonate the sulphate of lime is the next most abundant mineral in solution, and in some rivers forms nearly half the dissolved matter. The quantity in the

[1] "Address on Geological Time," Liverpool Geol. Soc., 1876. The proportion of the surface area of calcareous rocks in England and Wales is rather larger than that of Europe generally.

Thames water at Kingston is about one-sixth the total solids in solution, according to Professor Prestwich.

Less in amount are chloride of sodium, carbonate of magnesia, and silica. The proportion of silica found in river-water is believed to depend upon the concomitant amount of organic acids derived from the humus or vegetable soil occurring in the basin of drainage.[1] In the water of the Thames at London Bridge, the amount of silica is stated as ·1239 grains in a gallon,[2] or ·214 parts in 100,000; in the Rhine at Strasburg as much as 4·88 parts have been found.

Total Quantities of Transported Matter.—The calculations above given refer only to matter in solution; the total amount of matter carried down annually by any river can be estimated by examining its waters at different periods and determining their solid contents. The amount of matter carried down by any river in flood is very much greater than when the water is low, but Mr. Mellard Reade has pointed out that the amount in solution does not vary so much as that in suspension.[3] The Nile when in flood brings down 41 times as much matter in solution as it does during low Nile, but the amount in suspension varies, according to Dr. Letheby, from 4·772 parts per 100,000 at low Nile to 149·157 parts at high Nile, or 31 times as much, the flow of water being also increased about 26 times, so that the total amount brought down at high Nile is about 800 times as much as at low Nile.

In the case of the Danube the smallest delivery of suspended matter per day of twenty-four hours, is stated by Sir C. A. Hartley to be 11,000 tons, the greatest 2,500,000 tons,[4] or a variation of 227 times.

In order to make an exact calculation of this matter four things should be known regarding the river:—

1. The mean annual discharge of water.
2. The average amount of mud in suspension.
3. The average amount of coarser débris pushed along the river bottom.

[1] See Sterry Hunt, "Chemical and Geological Essays," pp. 126, 150.
[2] Ashley, in "Quart. Journ. Chem. Soc." vol. ii. p. 74.
[3] "On Rivers," "Trans. Geol. Assoc. Liverpool," 1882.
[4] Reade, *op. cit.*

4. The proportion of mineral matter in solution.

These data have not yet been all carefully obtained for many rivers, but some of them have been estimated in the case of several rivers, with the following results.

The Mississippi carries down every year about 6,724,000,000 cubic feet of sediment in mechanical suspension, and about 750,000,000 cubic feet more of sand and gravel is rolled along the bottom of its channel, making a total of about 7,474,000,000 cubic feet per annum. This would cover a square mile of ground to a depth of 368 feet. The amount in suspension only, calculated at 19 cubic feet to the ton, is equivalent to 354,000,000 tons per annum, and that rolled along is equivalent to about 39,500,000 tons per annum. The amount carried in solution has been calculated by Mr. Mellard Reade from an analysis of water taken a few miles above New Orleans, which gave 15·487 grains per American gallon, in which there are 56,000 grains of water. On this basis he estimates that the river carries 150 millions of tons of soluble matter per annum past New Orleans.

According to the observations of Sir C. A. Hartley on the Danube, the average amount of matter carried in suspension by this river may be put at 67,760,000 tons per annum; but the quantity rolled along the bottom has not been estimated. Neither has the amount in solution been accurately ascertained. Bischof gives an analysis of the water near Vienna, which yielded 12·42 parts per 100,000. Assuming this to be an average quantity, Mr. Reade calculates the total solids carried in solution past Vienna to be 22,521,434 tons per annum.[1]

The Rhone has been estimated to discharge 600,381,800 cubic feet of sediment per annum, which is equivalent to about 30,000,000 tons, but this is probably rather too great. Experiments at Arles gave the mean proportion of suspended matter in the river by weight as $\frac{1}{2000}$, and as the annual discharge of water at Avignon is estimated at about 53,144,000,000 tons, the quantity of suspended matter calculated from this should be 26,572,000 tons per

[1] Reade, "Denudation of the Two Americas," Geol. Soc. Liverpool, 1875.

annum. With regard to the matter in solution, the mean of four analyses given by Bischoff is 15·6, which as calculated by Mr. Reade gives 8,290,464 tons per annum.

The Nile is stated by M. Talabot to discharge at the rate of about 88,500 millions tons of water a year. Mr. Fowler estimates it at 100,000 millions, and states the amount of sediment carried to be 67 millions of tons a year.[1] Dr. Letheby found the amount in solution to vary from 13·614 to 20·471 per 100,000 in 1874; if we assume the mean to be 17 parts, and take Mr. Fowler's estimate of discharge, we find the amount of matter carried by the Nile in solution to be 16,950,000 tons a year.

The amount of suspended sediment carried by the Thames has never been estimated, except on the assumption that the proportion by weight to that of the water is the same as that of the Mississippi, in which case the amount would be 982,000 tons a year. The amount in solution has been given by Prestwich as 548,230 tons.

Tabulating the above statements and calculations we have—

Mississippi.	In suspension	=	354,000,000 tons.
	Along bottom	=	39,500,000 tons.
	In solution	=	150,000,000 tons.
	Total		543,500,000 tons.
Danube.	In suspension	=	67,760,000 tons.
	In solution	=	22,521,434 tons.
	Total		90,281,434 tons.
Nile.	In suspension	=	67,000,000 tons.
	In solution	=	? 16,950,000 tons.
	Total		83,950,000 tons.
Rhone.	In suspension	=	26,572,000 tons.
	In solution	=	8,290,464 tons.
	Total		34,862,464 tons.

[1] "Brit. Assoc. Rep." 1882, Address to Mech. Sec.

Thames.	In suspension =	? 982,000 tons.
	In solution =	548,230 tons.
	Total	1,530,230 tons.

Erosive Power.—That running streams have the power of deepening and widening the channels in which they flow, is now a well established and most important fact. The power of running water to cut out a channel for itself is often well exemplified on a newly-made bank of earth or sand, before it becomes covered with vegetation. If such a bank of earth is observed after a shower of rain, it will be noticed that the slope is furrowed from top to bottom by little runnels and channels, which have been excavated by the rills into which the rain-drops collected as they coursed down the slope. This is a miniature representation of what takes place on the sides of a valley or the slopes of a watershed.

Sir Charles Lyell describes a ravine near Milledgeville in Georgia, U.S., entirely formed by the torrential action of rain-streams consequent upon the cutting down of the forests, which had previously prevented the rain from collecting into large streams. When the land was cleared cracks 3 feet deep were caused by the heat of the sun; and during the rains the rush of water deepened the principal crack at its lower extremity, whence the excavating power worked backwards, till, in the course of twenty years, a chasm was produced no less than 55 feet deep, 300 yards long, and varying in width from 20 to 180 feet.[1]

Miss Bird, describing a journey during heavy rain in the Sandwich Islands, says: "In some places several feet of soil had been washed away, and we passed through water-rents, the sides of which were as high as our horses' heads, where the ground had been level a few days before."

The process may also be studied with great advantage on the slopes of volcanic cones which have ceased to be active. An excellent set of examples has been described by Professor Jukes in the cluster of cones which have been built up inside the great crater of the Bromo in Java. Mr. Jukes

[1] "Principles of Geology," tenth edition, vol. i. p. 344.

says:[1] "One thing which struck me particularly in this central group of cones (in the crater of the Bromo) was, that the one in action was perfectly smooth and regular outside, like a loaf of sugar, while those that had shortly ceased to eject materials showed the irresistible progress of denudation in the commencement of rain-gullies radiating down their slopes. Those that were still older, as proved by young trees having commenced to grow on their flanks, had these gullies much deeper and broader, so that they began to show narrow ridges, separated by small ravines radiating from the summit, like the ribs of a half-opened umbrella, as described by Junghun, when speaking of the outer slopes of the greater mountains."

In the same way, the outer slopes of the volcanoes in the South Pacific, described by Dana, are worn down to the condition of narrow ridges, with very steep walls, separated by flat-bottomed valleys, which gradually contract towards the interior; and at the head of each valley may be seen a little rill of water leaping from crag to crag, still carrying on the work of erosion for which, except in times of flood, it seems so utterly inadequate.

It is not the mere force and impact of the descending water which gives a stream this excavating power; it is the quantity of detritus, large and small, which it carries along and hurls against the sides and bottom of its channel. The fine sand and mud which the rain washes off the surface of the land, are the initial instruments of erosion; but in rapid streams and mountain torrents, the stones and pebbles which are rolled along the bottom, as well as the sand and mud which are held in mechanical suspension, all help in the process of erosion. This process is therefore one of mechanical wear; the tools are pebbles, sand, and mud, the effective force which moves them is that of running water.

Vertical Erosion.—The erosive action of mountain torrents can hardly fail to be perceived by anyone who visits them and observes the beds of their narrow channels. These exhibit smooth grooves and cuts even in the hardest rocks, which are obviously due to attrition; while vertical

[1] "Manual of Geology," third edition, p. 353.

pits, called *pot-holes,* several feet in depth, are often formed in such rock by the whirling action of water keeping a few pebbles or a little coarse sand in perpetual circular motion. Cascades and waterfalls dig deep holes and black pools below the ledges over which they fall; these ledges, indeed, are often undermined by the dashing water, and are broken off, block by block, so that the cataract recedes farther and farther back; while a deep ravine is left in front, extending from the present falls to the point where they originally commenced. Niagara is an excellent instance of such erosion, the gorge below the cataract being seven miles in length from the original site of the falls above Queenstown to their present position; and the present rate of their recession has been recently estimated at about three feet per annum.

Pot-holes and waterfalls illustrate the excavating power of running or falling water when its action is concentrated on one spot, but similar wear and tear distributed over a certain length of the channel will deepen it in the same way.

Lateral Erosion.—Mr. J. Fergusson has defined a river as a body of water in unstable equilibrium, whose normal condition is that of motion down an inclined plane; and he says, if all inequalities of surface and of soil could be removed, it would flow continuously in a straight line, "but any inequality whatever necessarily induces an oscillation, and the action being continuous, the effects are cumulative, and the oscillation goes on increasing till it reaches the mean between the force of gravity tending to draw it in a straight line, and the force due to the obstruction tending to give it a direction at right angles to the former."[1] The result is a series of curves which, in a homogeneous soil, would bear definite relations to the volume of water and the gradient of the channel.

It may be stated in general terms that where the slope is steep the stream will tend to run in a nearly straight line; and where the slope is slight, a stream will always

[1] "Quart. Journ. Geol. Soc." vol. xix. p. 322. He proceeds to lay down certain laws of curvature which, however, are not practically applicable, though no doubt where other things are equal a large river makes a larger curve than a smaller river would.

take a very winding course. It is also true that there is a point in the descent of every stream where it ceases to cut vertically, and is occupied in cutting laterally. No rule can be given about the position of this point, because it is determined by the velocity of the current, and this varies with the state of the river; and some streams may begin to cut laterally before they cease to cut vertically; but for a given stream at a given time, the place of change might be approximately determined by observation and the gradient noted.

Wherever a river cuts laterally, and not vertically, it is continually changing its channel, and always leaves a flat of deposited detritus over the portion of its channel which it has deserted. The result of this is to cut out a broad space, and to form a wide flat-bottomed valley, the width of which is generally proportional to the volume of the river. When the river is in flood, it covers the whole of the flat, which is often called the *flood plain*, but, when the water is low, the stream winds about within this flood plain.

After winding in a flood plain for a certain distance, a river may reach a part of its course where the gradient is steeper, and will then resume the power of deepening its channel. Hence many rivers run through an alternating succession of deep-cut gorges and wide open valleys; but the subject of valley-making will be discussed more fully in Part III. of this volume.

It must not be supposed, however, that the depth and width of a valley depend only on the volume and velocity of the stream; as long as the rocks through which it makes its way are of the same kind and degree of hardness, its erosive effect will be chiefly regulated by these conditions. But where, as usually happens, the valley traverses a series of different strata, its width and depth will vary according to the hardness and ability of each stratum to resist the erosive action of the stream, and the detritive power of rain.

In a humid climate like that of England and of northern Europe generally, and in districts where the rocks are comparatively soft, the valleys are broad and open, with gently sloping sides, and the hills have rounded outlines forming binomial curves.

These features are due to the disintegrating and detritive effects of rain on the valley-sides; the action of rain and frost, already described, causes the banks to crumble and moulder down, and every heavy shower of rain washes some of the soil so produced into the stream below, by which it is carried away to be deposited elsewhere.

In such districts, therefore, rain has as much to do with the formation of valleys as the rivers have,[1] and the valleys which are formed by the combined influence of these two agencies are always widely V-shaped, the sides sloping at a less angle in proportion as the rocks are soft and the rainfall great.

On the contrary, where the rocks are hard, the erosive action of the stream tends to excavate narrow steep-sided

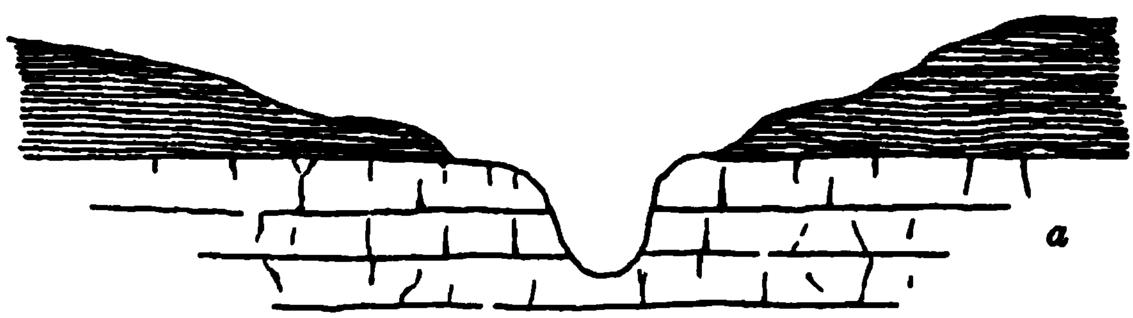


Fig. 35. Erosion of Valleys.
a, hard rock. *b*, soft shale.

valleys or U-shaped gorges, the sides of which approach the vertical in proportion as the rock is hard and the local rainfall is small.

In places where a softer kind of rock rests upon a harder one, the valley will present a combination of the two forms as represented in fig. 35.

When the banks are soft and easily eroded, and the velocity of the stream is small, the conditions are most favourable for lateral erosion, and a wide, flat-bottomed valley, filled with alluvial detritus, is the result. This is well exemplified by the lower part of the valley of the Mississippi, where the stream has lost all power of vertical erosion, and pursues its meandering course through an alluvial plain of its own formation, which varies from 50 to 80 miles in width.

[1] See "Rain and Rivers," by Col. G. Greenwood, 1875.

Rapidity of Erosion.—From what has already been stated, it will be seen that the erosive power of any stream —*i.e.* the quantity of material which it can remove from its valley—depends upon four circumstances—

1. The volume of water, depending upon the annual rainfall, frequency of floods, and the porosity of the soil;
2. The velocity of stream, depending on the volume of water, and the slope of the watercourse;
3. The character of the rocks through which it flows;
4. The load or quantity of detritus which it carries.

In considering the work done by rivers we must always remember that the running water is only the motive power, and that the instrument which really does the work is the sand and mud carried along by the water. A perfectly clear stream running over a bottom of pebbles which it does not move is doing no work at all; it is only when loaded with detritus that it becomes such a powerful agent of erosion.

The facts previously stated show how much the capacity of a stream for lifting and carrying stones is increased by a slight increase of velocity, and their power of erosion must, of course, be correspondingly increased. Mr. A. Tylor has stated that the erosive force of a stream increases as the fourth power of the increase of velocity.[1] If this is correct,[2] and his law of increase of velocity, previously cited, is also valid, the result may be stated as follows:—

Supposing a sudden rainfall to take place in the catchment area of a river, increasing the volume of the stream to eight times its usual quantity, the velocity would be doubled and the river would have 16 times its ordinary erosive force; if the volume was increased 27 times, the river would flow with 3 times the velocity, and with 81 times its former erosive force. This explains the astonishing effects of rivers in times of flood. Large boulders are then moved, stones and pebbles are driven against the sides

[1] "Geol. Mag." Dec. 2, vol. ii. p. 459.

[2] It is confirmed by Le Conte, "Geol. Mag." Dec. 2, vol. ix. p. 288, who points out that in erosion the resistance to be overcome is cohesion, not weight, and thinks the power of removal will vary between v^2 and v^6, so that it is probably often as v^4.

and bottom of the channel, and the whole work of attrition and excavation is carried on with greatly intensified force.

Sir Charles Lyell remarks: "It is evident, therefore, that when we are speculating on the excavating force which a river may have exerted in any particular valley, the most important question is, not the volume of the existing stream, nor even the nature of the rocks, but the probability of a succession of floods at some period since the time when the valley may have been first elevated above the sea."[1]

In temperate regions these are exceptional occurrences; but, in tropical countries, floods are of constant occurrence during the rainy season; consequently the erosive power of the streams is enormously increased, and all the results of detrition are on a much larger scale. As this is a fact which European geologists do not always realize, we adduce the testimony of one whose experience well qualified him to express an opinion on the subject:[2]—"In the British Islands, the average rainfall is about 24 inches, distributed over the greater portion of the year. In India it averages about 50 inches, by far the greater portion of which falls in three months. The showers are far heavier, and far more effective in sweeping soil, sand, and pebbles from the surface of the country into the streams; and floods in the latter are of annual occurrence, instead of only happening at rare intervals. The effect of a river in full flood, in sweeping detritus down into the sea, compared with the usual denudating action, is as the comparison of the effect produced by the breakers of the ocean in a storm to those of an inland sea on an ordinarily fair day.

"In flood, a river is liquid mud, rather than water. But, in addition to the great floods, minor floods in tropical streams are matters frequently of daily occurrence during the rainy season. After seeing, both in India and Abyssinia, what the effects of these agents are in tropical countries, I do not feel surprised that their powers should be recognized with difficulty in regions where their effects are comparatively so dwarfed as in the British Isles."

Heavy and destructive floods however do sometimes

[1] "Principles of Geology," tenth edition, vol. i. p. 354.
[2] Blanford, "Geology and Zoology of Abyssinia," p. 157, note.

occur in Europe and the British Isles, and others have been caused by the bursting of reservoirs, and though this is not a natural cause, the results are of the same kind. The following instances will enable the reader to realize these results more fully.

1. Professor Green mentions some results of a flood which was caused by the bursting of a reservoir near Sheffield, in 1864. He says: "At sharp bends in the valley, where the water had impinged on projecting spurs of the bank, or where it had been driven into a recess, it had excavated in the solid sandstone rock large hollows, which anyone, who was not aware of the circumstances of the case, would have supposed to be quarries. Many acres of meadow-land were deeply buried beneath heaps of débris, consisting mainly of large angular blocks of rock, which the torrent had torn off from the banks as it rushed along."[1]

2. Sir Charles Lyell has described the destruction worked at Tivoli by the waters of the Tiber, after heavy rains, in 1826. The stream burst its usual bounds, and, impinging on its right bank, had, in the course of a few hours, undermined a high cliff, and widened its channel by about 40 feet. The church of St. Lucia, and about thirty-six houses of the town of Tivoli, were carried away, presenting, as they sank into the flood, a terrific scene of destruction to the spectators on the opposite bank."[2]

3. Lyell also mentions the Alpbach, a torrent which falls over a cascade near Meyringen in Switzerland, and is liable to violent floods, by one of which the town was nearly washed away. "This mischief happens after long droughts, when the sun has had great power on the slate rocks above, and caused them to crack and decompose. Those who have not witnessed it cannot conceive the strength of water charged with this black powder. The rocks seemed actually to float in it, and a trifling depth of it was pushing heavy bodies along."[3]

4. Floods in Scotland, 1829.—Many illustrations of the

[1] See Prestwich, in "Quart. Journ. Geol. Soc." viii. p. 224.
[2] "Principles of Geology," tenth edition, vol. i. p. 355.
[3] "Life of Sir Charles Lyell," vol. i. p. 85.

power of rivers to move stones, and deepen or widen their valleys, were afforded by the floods which followed the storm of the 3rd and 4th of August, 1829. The effects were particularly apparent in Aberdeenshire. Bridges and roads were swept away, and great accumulations of stones and blocks of rock were left on the surface of fields, many feet above the ordinary level of the rivers. "Some new ravines were formed on the sides of mountains where no streams had previously flowed; and ancient river-channels, which had never been filled from time immemorial, gave passage to a copious flood."

Instances of River Erosion.—Having in the preceding pages indicated the manner in which streams excavate and widen their channels, and the causes which assist rivers in forming the valleys they occupy, we shall now describe several cases in which it is clear that ravines and valleys have been formed by rivers. The ravine at Milledgeville, described by Lyell, and mentioned on p. 136, is an instance of the excavating power of a stream formed by the concentration of rills of rain-water. The observations of Professor Jukes, in Java, furnish us with an equally convincing example.

The following are cases of river-valleys where the excavating power of running water is very clearly shown.

1. *Gorge of the Simeto.*—Near the town of Aderno, where the river Simeto passes the western base of Etna, a current of lava has descended into the valley, and, in so doing, must have completely blocked up the course of the river. This took place, according to Gemmellaro, in the year 1603. Through this lava, which solidified into a hard, blue compact rock, resembling ordinary basalt, the Simeto has excavated a ravine from 40 to 50 feet deep, and from 50 to several hundred feet wide. Sir Charles Lyell thus describes the scene in 1828: "On entering the narrow ravine, we are entirely shut out from all view of the surrounding country; and a geologist, who is accustomed to associate the characteristic features of the landscape with the relative age of certain rocks, can scarcely dissuade himself from the belief that he is contemplating a scene in some rocky gorge of very ancient date. But the moment we reascend the cliff, the spell is broken . . . for we stand

on the black and rugged surface of a vast current of lava, which seems unbroken, and which we can trace nearly up to the distant summit of that majestic cone which Pindar called the 'pillar of heaven.'" [1]

This ravine, therefore, has been eroded by the stream in the course of about two centuries; but, as Lyell observes, it has not yet cut down to the ancient bed of which it was dispossessed, and the probable position of which he indicates in a diagram.

2. *Valleys of Auvergne.*—What has happened once in the case of the Simeto has happened several times in many of the valleys of Central France. These valleys have been excavated to a great depth through strata of fresh-water origin, and have been flooded from time to time by streams

Fig. 36. Diagram Section across Valley of Chanonat, Auvergne. *a*, the Gergovia platform. *b*, the La Serre platform. *d*, the Chanonat gorge.

of liquid lava from the neighbouring heights. Each successive lava-flow must necessarily have occupied the lowest levels to which it had access; but they now form terraces or platforms at various heights, from 1,500 feet downwards to the level of the present watercourses. These valleys were originally described by Mr. Poulett Scrope, who says: [2] "Take, for instance, the two basaltic platforms of Gergovia and La Serre, and the bed of basalt which occupies the bottom of the intervening valley of Chanonat. Here are three long sheets of lava, each of which, by its gradual inclination in the same direction, and by the remains of the volcanic vent from which it was erupted, is proved to

[1] "Principles of Geology," tenth edition, vol. i. p. 358.
[2] "The Volcanoes of Auvergne," 1825, and "Geol. Mag." vol. iii p. 195.

have flowed down the valley." The platform of La Serre is everywhere from 300 to 500 feet below that of Gergovia, and the valley must have been deepened by that depth during the interval between the two outflows. Again, by the same reasoning, the valley of Chanonat must have been entirely excavated between the epoch of the La Serre lava and the production of the more recent bed of basalt, 500 feet below. Finally, the Chanonat rivulet has worn a new channel, from 20 to 50 feet below the level of the pebble bed on which the most recent of the three lava currents reposes (see fig. 36).

From this and numerous other instances, he justly concludes that "the erosive force of the streams which now border or intersect these lava currents, together with the action of rain, frost, and other atmospheric forces, have alone hollowed out the extensive systems of valleys" which are found in the province of Auvergne. Floods doubtless occurred from time to time, and materially assisted in the erosion; but it is very clear that these valleys do not owe their origin to any one unusual or cataclysmal flood, or to any sudden disruption of the rocks.

Sir A. Geikie has so excellently described the impression which the valleys of Auvergne make upon the mind of a geologist, that I venture to quote several passages in full:—

"No one, whose observations have been confined to a country which has been above the sea only since the glacial period, or the contours of which have been smoothed over by the ice-sheets of that time, can readily form an adequate idea of the denuding effect of water flowing over the surface of the land. . . . The first impression received from a landscape, like that round Le Puy, is rather one of utter bewilderment. The upsetting of all one's previous estimates of the power of rain and rivers is sudden and complete. It is not without an effort, and after having analyzed the scene, feature by feature, that the geologist can take it all in. But when he has done so, his views of the effects of subaerial disintegration become permanently altered, and he quits the district with a rooted conviction that there is almost no amount of waste and erosion of the solid framework of the land, which may not be brought about

in time by the combined influence of springs, frost, rain, and rivers." [1]

3. *Valleys of the Eifel.*—The country of the Lower Eifel, where it is traversed by the rivers Rhine and Moselle, affords another excellent instance of the excavation of valleys by river erosion. The country is composed of beds of hard rock, bent and inclined in various directions, and the general surface forms a gently undulating table-land, about 1,000 or 1,200 feet above the level of the sea. Through this country the rivers flow at the bottom of deep and winding valleys, forming the magnificent curving slopes which are the chief feature in the scenery of the district. This is particularly striking in the case of the Moselle, which works its way in so tortuous a course that some of its bends form loops, and curve back, so as to leave but a narrow ridge between the two reaches of the river. This singularly winding valley is both narrow and deep, being closely environed by steep, precipitous banks, 800 to 1,000 feet in height; and between their opposing bases, there is frequently no more room than is just sufficient for the river itself.

The country on either side is furrowed by numerous naarrow ravines, with steep and often precipitous sides, which cut down, as they near the Moselle, to depths of 600 or 800 feet below the surface of the plain, and curve from side to side in equally sinuous courses.

The only explanation which can be given of such a wonderful system of valleys is that the streams originally ran over the surface of the plain, and have constantly maintained the winding courses of their early channels, gradually engraving them deeper and deeper into the land, as the work of erosion and excavation proceeded. The action of rain has been co-extensive with that of the streams, wearing down the valley sides, and widening them into the shape they now possess.

4. The most wonderful instances, however, of the erosive power of rivers are to be found in the deep and trench-like valleys of the Western States of North America.

The Colorado is formed by the union of the Green and

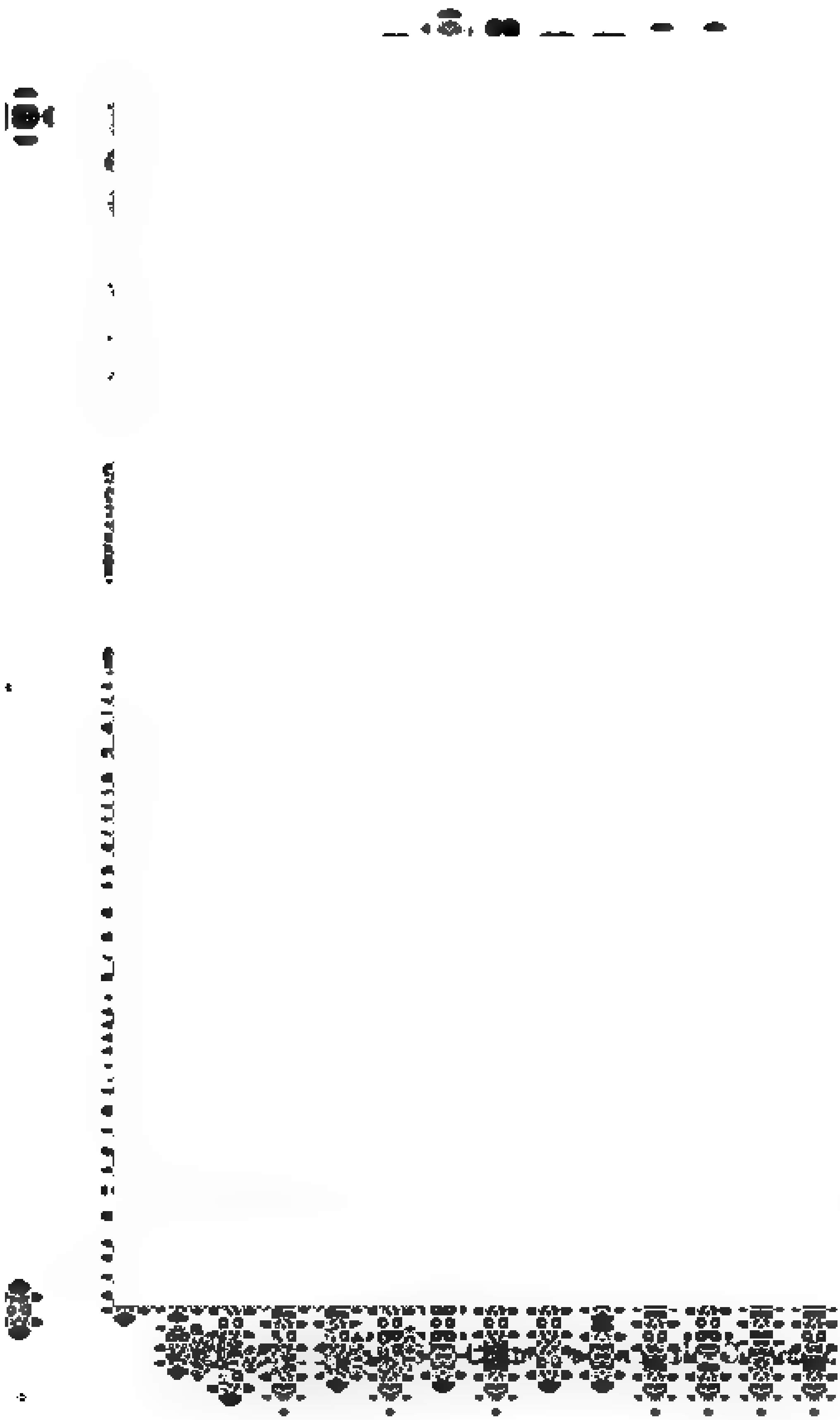
[1] "Geological Sketches," by A. Geikie, 1882, pp. 93, 121.

Grand Rivers, but the Green River may be regarded as the continuation of the main stream. This rises in Wyoming, and is joined by the Grand in Utah, whence the Colorado runs through Utah and Arizona to the Gulf of California. The Uinta Mountains are traversed by the Green River in a double series of gorges (or cañons), the deepest parts of which have walls from 2,000 to 2,500 feet high. Then, after running through a more open valley, the river traverses three great inclined plateaux, in a series of cañons which have received the names of Desolation, Gray, and Labyrinth Cañons. It then enters Stillwater Cañon, and in this, more than 1,200 feet below the general surface of the country, the Green and Grand Rivers unite their waters.

The Colorado, below this junction, at once enters Cataract Cañon, and proceeds through a still more wonderful and gigantic series of gorges, which have received the names of Glen Cañon, Marble Cañon, and Grand Cañon. Glen Cañon is 149 miles long, but is not very deep; Marble Cañon is only 200 feet deep at its head, but steadily increases in depth, till near the lower end its walls are 3,500 feet high, and present a magnificent set of precipices, which in some parts are nearly vertical.

The Grand Cañon is about 220 miles long, and is really a valley within a valley, consisting of an upper trough or depression eight to ten miles wide, with a level floor and precipitous sides about 1,000 feet high, and an inner gorge or cañon which varies in depth, but is in several places from 4,000 to 5,000 feet deep, its walls being a succession of vertical precipices broken only by short steep talus-slopes. One of the deepest and finest parts of this cañon is represented in fig. 37. The country on both sides of this enormous ravine is channelled by innumerable narrow, deep, and winding cañons, all similar in their general characters, and each one occupied by a tributary of the main river.

These extraordinary ravines have been cut down through horizontal or gently-inclined beds of sandstone, shale, and limestone, and into the granite which underlies them, the limestones being especially hard and massive, with an aggregate thickness of from 2,200 to 2,500 feet. The shales and sandstones lie above these limestones, and it is



these beds which have been cut back so as to leave the broad shelf or plain on either side between the edges of the central ravine and the lines of cliff which bound the upper part of the valley. The outline of the whole valley is then similar to that in fig. 35, only that the edges of the upper portion are not sloping, but nearly vertical.[1]

The reason why these great ravines are such excellent instances of river erosion is because they were made almost entirely by the rivers alone, with little assistance from any other detritive agencies. The district drained by the Colorado and its tributaries is a series of elevated plateaux: and there is little doubt that, when the course of the river was first determined, the country stood at a much lower level, and the tributary streams ran in channels of no great depth. The cañon district is now from 4,000 to 8,000 feet above the sea, and the mountains which form the watershed rise to 10,000 and 14,000 feet. These snow-clad summits furnish a perpetual supply of water, which on reaching the plateaus above the cañons becomes charged with sand and mud.

Two circumstances have combined to maintain the verticality of the cañon walls during the process of erosion: the first is a decrease in the rainfall of the cañon district, for at the present time it is practically rainless, and we have seen that gorges are steep and narrow in proportion as the rocks are hard and the rainfall small; secondly, the beds through which they are cut are for the most part horizontal, or very gently inclined, and are traversed by strong vertical planes of jointing, so that they break away naturally in vertical lines.

The conditions which have enabled rivers to cut their way through what are now ridges and mountains, the forces which retard or increase their power of erosion, and the limits which are set to their action, are matters that will be discussed in the third portion of this volume.

[1] For descriptions and illustrations of these cañons, see "Exploration of the Colorado River," by Ives and Newberry, 1861, and the later "Memoirs" by J. W. Powell, 1875, and C. E. Dutton, 1882.

CHAPTER IX.

FLUVIATILE AGENCIES.

2.—*Action of Glaciers.*

FORMATION of Glaciers.—On high mountains and in high latitudes, as in Greenland or Lapland, the water precipitated from the atmosphere falls as snow instead of rain. This occurs even in the Torrid Zone wherever the land exceeds an altitude of 15,000 or 16,000 feet above the sea, and in all other latitudes at a less height in proportion to their distance from the Torrid Zone. In the Alps the snow-line in summer occurs at a height of 8,800 feet above the sea. Near the North and South Poles it comes down to the level of the sea. In regions of perpetual snow even the hottest summer's sun fails to melt all the snow that falls in a year, hence there is a continual accumulation of it, and, if there were no way of getting rid of it, all the water in the world would be eventually transferred to these regions and remain there in a solid form. There is, however, a drainage from these snow-covered regions by means of glaciers, just as there is a drainage from other regions by means of brooks and rivers. The lower part of all perpetual snow is being constantly converted into ice; the weight of the superincumbent mass forces out the air from between the snow-flakes and binds them together, just as a snowball is made harder by the pressure of the hand. This firm, granular kind of snow is known as *névé* or *firn*, and as it is pushed down the mountain slopes it passes into a kind of soft ice, partly in consequence of the pressure from above, and partly from the alternate melting and freezing of the surface layers: the

sun melts the surface in the daytime, and the water so formed percolates down into the mass and becomes frozen again below.

The ice thus formed is gradually pushed down into the valleys, along which it continues to travel in the form of ice-rivers or *glaciers*. The glaciers of the Alps are sometimes as much as 600 feet in depth, and they fill the valleys for many miles below the snow-line, till they come down to a level of about 3,500 feet below it, where they terminate, in consequence of the ice melting into water and proceeding as a brook or a river. In the New Zealand Alps, where the summer snow-line is at about 5,000 feet, the glaciers on the Mount Cook range, near lat. 44, descend to about 2,300 feet on the eastern side, and one on the western side comes down to within 670 feet of the sea, discharging its load of débris in the midst of a sub-tropical vegetation.[1] In high latitudes, where the snow-line is near the sea-level, the ice is pushed into the sea, and the portions which break off from time to time are floated off as icebergs.

Movement of Glaciers.—Glaciers creep along their beds at a rate which varies with the supply of ice, the slope of the valley, and the season of the year, but their movement is seldom so rapid as to be perceptible without careful measurement. Like a river, the ice moves faster in the centre than near the sides, and the surface layers move faster than the lower portions, and the whole moves as if it were a plastic or viscous body. The lower parts of the Swiss glaciers, where the gradient is not steep, only move at the rate of one or two feet in 24 hours; thus the Mer de Glace in summer moves at an average rate of 27 inches a day in the centre, and from 13 to 19 inches a day near the sides; in the winter the rates are only about half as much. Where slopes are very steep ice-falls are formed, the ice descending in huge steps or slices, with long fissures or crevasses between, but on reaching a gentler slope the fissures close and are frozen together again. Such ice-falls are frequent in Norway.

Where there are large snow-fields, and the glaciers pass

[1] Green's "High Alps of New Zealand," 1883, p. 75.

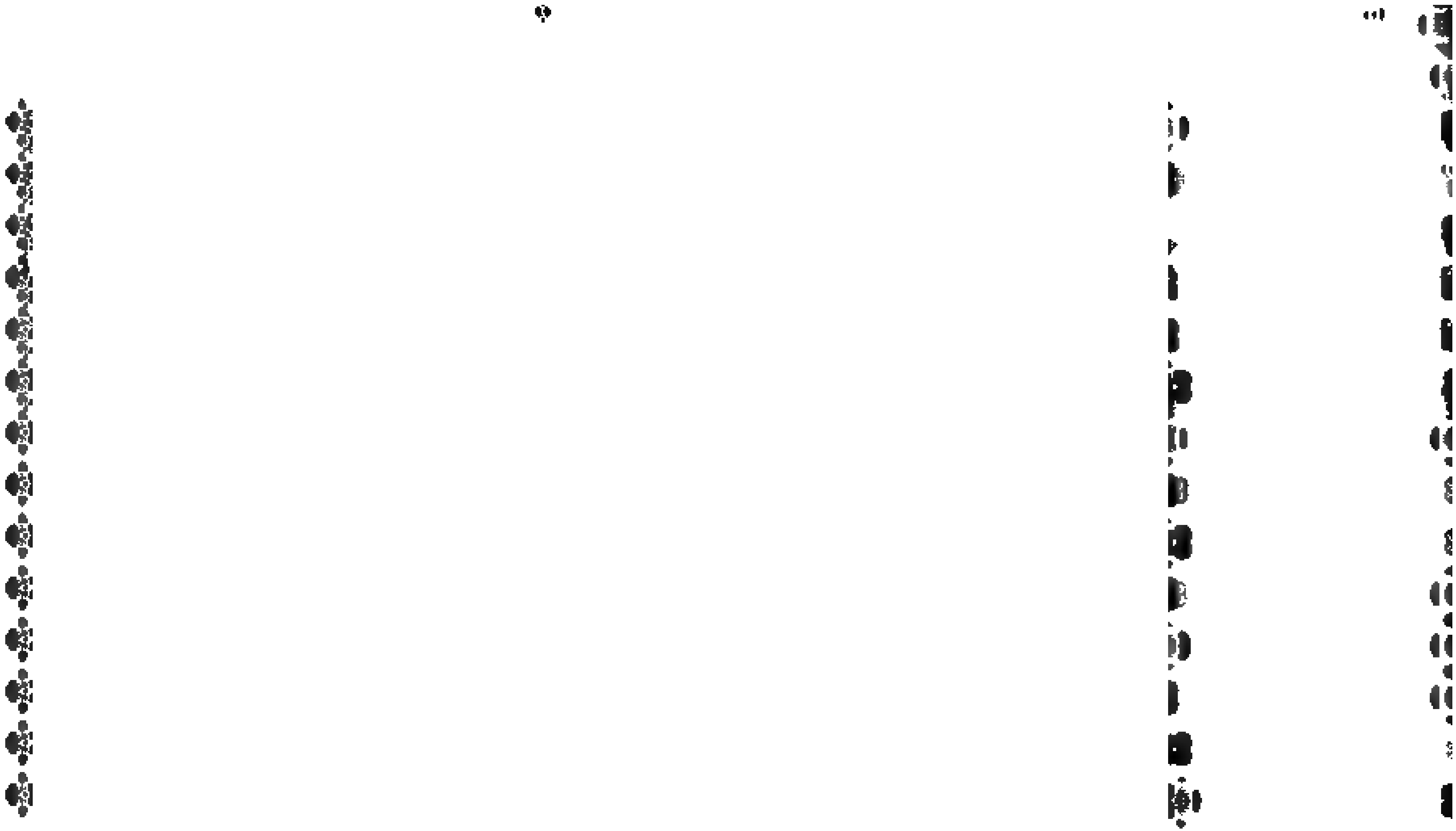


Fig. 38. Ideal representation of a Glacier.

down fairly steep slopes, their movement is much faster than any of the Swiss glaciers. Thus at Glacier Bay, in Alaska, nine large and seventeen small glaciers unite to form an ice-stream which has a front of 5,000 feet in width and a depth of 700 feet where it enters the bay: this stream moves during August at the rate of 70 feet a day in the middle, and 10 feet near the sides.

Transport by Glaciers.—We have seen that, in the case of rivers, two processes are going on at the same time, namely, erosion and transportation; the rivers of ice perform the same kind of work, but in a different way. Wherever a glacier passes beneath a crag or cliff of rock it receives on to its surface a continued supply of blocks and stones which are detached by the action of frost and weathering, described on p. 102. A line of such rock-fragments may generally be seen at each side of the glacier. Where two glacier-streams unite the two lines of transported stones on their adjacent sides come together and form a double median line along the centre of the glacier below the junction of the two valleys. Thus, if a glacier happen to have many important tributaries proceeding from different valleys, and uniting to form one large ice-stream, this may come to have many separate lines of stones and rubbish, which are all carried along to the place where the glacier terminates. Here they are all thrown down, and form an irregular mound or pile of rough, angular débris mixed with earth, which in Switzerland is called a *moraine*. This term is also applied to the lines of stones on the glacier, so that there are three kinds of moraines, *lateral*, *medial*, and *terminal*. (See fig. 38.)

Very large blocks of rock are sometimes transported by glaciers to great distances from their parent sources, and in those countries where the glaciers were once larger and longer than they are now, such blocks are found scattered over the area formerly covered by the ice; they are often perched on eminences, or left stranded on the sides of a valley. Rock-masses found in such positions are called *perched blocks* or *erratics*. (See fig. 39.)

Some of the clearest and best-known instances of the transport of such blocks are found in Switzerland. There was a time, generally known as the *Glacial Period*, when

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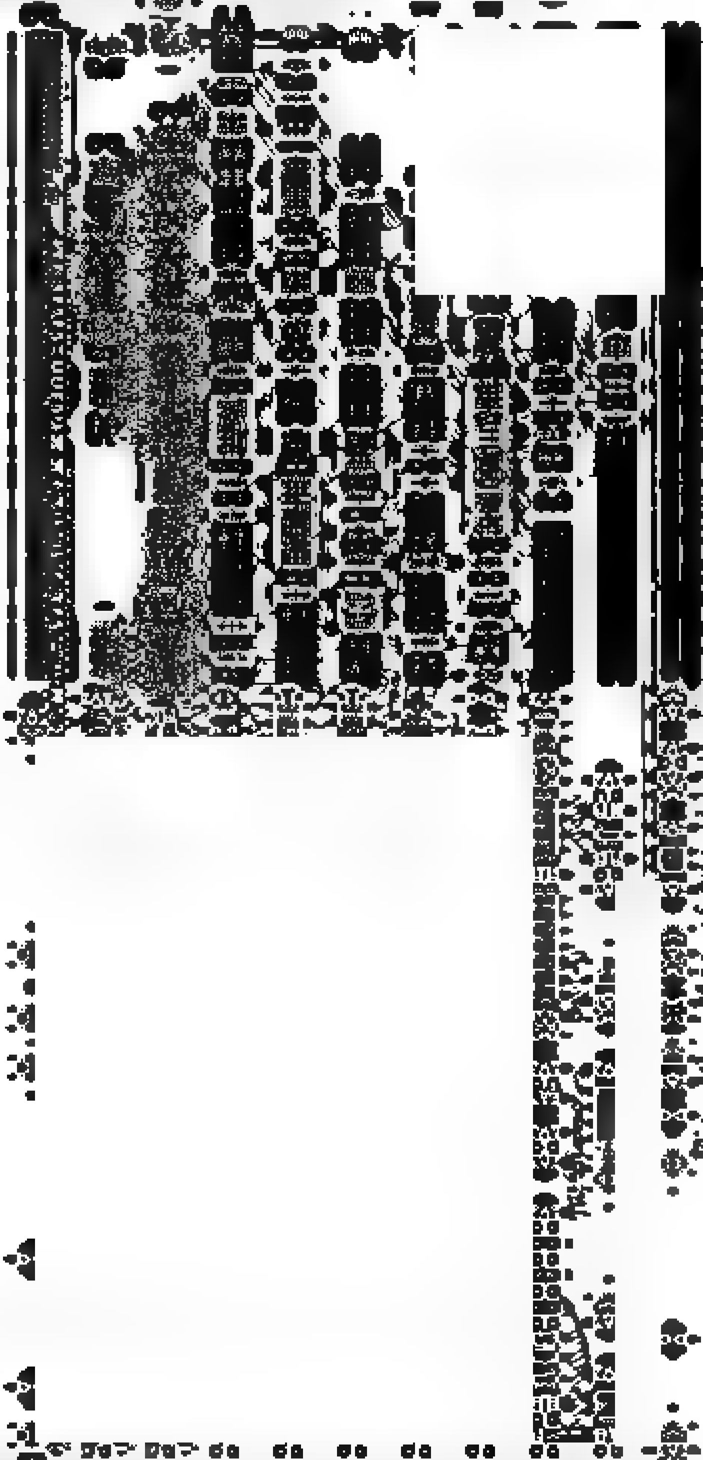

Fig. [illegible]. Map of the old Glaciers of Northern Switzerland.

1. Arve glacier.
2. Rhone glacier.
3. Aar glacier.
4. Reuss glacier.
5. Rhine glacier.

... not always ... and broken,

and sometimes it is traversed by deep cracks or clefts called crevasses. Many stones and blocks fall down these, others are picked up from the bed of the glacier and get firmly frozen into the ice. The stones thus fixed in the under surface of a glacier scratch and groove and wear away the rocks over which they are moved, and are also scratched and worn themselves by the hard projections of the rocks beneath. One result of this action is the production of a quantity of fine mud and sand, so that if a lump of glacier ice is dissolved in a glass of water, it makes the water as turbid as if a spoonful of milk had been put into it. The river that always springs from the end of a glacier carries away all this mud, and flows as a dirty yellowish or greenish white stream, until it reaches the sea or some great lake in which the sediment may be deposited.

It must not be assumed, however, that all the mud in the stream which issues from the end of a glacier is the result of erosion by the ice. Some of it is earth which has fallen on to the ice with the stones of the moraines, and in summer there are always streams of water which course over the surface of a glacier till they plunge into a crevasse; frequently also springs issue from the rocks below the ice. In this way a sub-glacial river comes to be formed, which flows beneath the ice, and acts like other rivers in eroding its channel.

One marked and characteristic result of the grinding and rasping action exercised by a large glacier is the wearing and rounding off of all the prominences over which it passes, and a general smoothening and polishing of the rocky surfaces, so as to produce a peculiarly moulded outline, which is quite different from the surface features produced by any other agency. If we examine a valley where the glacier once extended much further down than it does now, we shall find that the ice has left a smoothened surface of rock, rising here and there into rounded bosses or hummocks, which have a smooth, polished, and gently sloping surface on one side, with a rougher and steeper slope on the other; we shall also notice that the smoother faces of these hummocks all look up the valley towards the quarter whence the moving ice came. When viewed from a distance they have been thought to bear some resem-

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It has even been suggested by Sir A. Ramsay that the rock basins in which many lakes lie have actually been excavated by the erosive action of the glaciers; on this point, however, there is much difference of opinion among geologists; and none of the facts brought forward by Ramsay in support of his view can be regarded as proving its truth. Thus it is a fact that lakes are most numerous in those countries which are known to have been swept by the ice of the Glacial Period; but the rock basins in which these lakes lie may have been pre-existent, and have simply been cleared out by the glaciers in the manner just described. The fact that glacial striæ can be traced through these rock basins is no proof that the ice made the hollows. Lastly, glaciers probably have most erosive power where the ice is forced through narrow defiles and down steep slopes, and not, as Ramsay imagined, where they impinge on gentle slopes or plains.

Actual observations seem to show that where a glacier reaches a level space it does not exercise any erosive power, but, if it is advancing, it may override its own moraine, without ploughing through it. Professor J. W. Spencer has described several glaciers in Norway, which, though advancing, are not doing any erosive work. He found that a very slight ridge of rock was sufficient to divert the flow of the ice; and that large stones, instead of being held fast, and used as grooving tools, often left a groove or furrow in the ice which had passed over them. It must be remembered, however, that the erosive power of a glacier must be greatest where the ice is thickest and the rate of movement greatest, whereas at its terminal extremity the ice is thin and the movement slow.

Glaciers do not cut in rock!

Ice Sheets.—In Arctic and Antarctic regions, where precipitation is always in the form of snow, and the summer sun never melts all the winter snow-fall, the snow accumulates to such an extent as to cover large areas of land, and to form massive ice-sheets which may be several thousand feet thick.

Greenland is covered by such a mantle of ice and snow, and this has recently been traversed from one coast to the other by Dr. Nansen, who thus describes it: "The ice-sheet rises comparatively abruptly from the sea on both

sides, but more especially on the east coast, while its central portion is nearly flat. On the whole the gradient decreases the further one gets into the interior, and the mass thus presents the form of a shield, with a surface corrugated by gentle, almost imperceptible, undulations, lying more or less north and south." The highest part is about 9,000 feet above the sea, and rather nearer the east coast than the west. How far this ice-sheet extends toward the north is not yet known; but Dr. Nansen remarks that its limit must lie beyond the 75th parallel, for so far along the west coast it sends huge glacier arms into the sea. Among these is Upernivik Glacier, which moves down at the rate of 99 feet in twenty-four hours. The thickness of this ice-sheet in the interior cannot, of course, be estimated; but no mountains rise above it, and those parts of it which come near the coast are considered to be from 2,000 to 3,000 feet thick.

On the western side of the country the edge of the inland ice is from 50 to 100 miles from the coast; but on the east coast large portions of it descend into the sea, and the peaks of nearly buried mountains (*nunutaks*) can be seen projecting above its surface, and only small tracts near the shore are free from ice. Both coasts are indented by fiords, the upper ends of which are generally barred by the ice-cliffs in which the huge glaciers terminate, and from which icebergs are being continually given off.

Nansen gives a section across South Greenland which shows the surface contour of the inland ice, but he makes no attempt to indicate the form of the ground beneath, though his observations afford some data for doing so. Thus the mountain peaks which rise through the ice near the east coast were all from 3,000 to 4,000 feet high, and between 40 and 50 miles inland he saw several *nunutaks* with elevations of over 6,000 feet. On the west coast the highest ground is often near the sea, and away from the inland ice, though in places this is parted by peaks and ridges from 2,000 to 3,000 feet high. The diagram, fig. 42, has been drawn in accordance with these indications, and will at any rate serve to give some idea of an ice-buried country. Fig. 43 is a portion of the inland ice descending to the sea as a glacier.

Fig. 43. View of a Glacier descending from the Inland Ice of Greenland.

The interior of the island of Spitzbergen is also covered with a snow-field and ice-sheet from which huge glaciers descend into the sea; indeed, some parts of the coast consist almost entirely of the ice-cliffs in which the glaciers terminate. Mr. J. Lamont has described a glacier on the south-east coast which has a continuous front of ice 30 miles wide, and projects into the sea in three great semicircular divisions, the largest of them protruding for three or four miles beyond the real coast-line. The frontal ice-cliffs of this glacier vary from 20 to 100 feet in height, and from them masses of all sizes—up to that of a church—are continually breaking off and crashing into the sea. The two outer lobes consist of smooth ice, but the inner one is so rough and jagged that, when seen dimly through the fog, "it resembles more than anything else a forest of pine-trees covered with snow."

The terminal position of some of these glaciers appears to vary; some have advanced and others retreated since they were first observed. Nordenskiold states that in Bell's Sound there was in 1858 a harbour, at the head of which was a strip of lowland, and beyond this a low but broad glacier. In 1860-61 the glacier advanced over the lowland, filled up the harbour, and extended far into the sea. "It now constitutes one of the largest glaciers in Spitzbergen, from which immense blocks of ice constantly fall down, so that not even a boat can venture in safety beneath its broken border."[1]

Mr. Lamont says that many of the bergs which floated away from the ice-cliffs of Spitzbergen "were heavily charged with clay and stones," and that the sea for miles around is sometimes discoloured from the quantity of mud which is washed off this floating land-ice by the waves, and brought down by the torrents which elsewhere descend from the mountains.

Where mountains rise through an ice-sheet, lines of surface moraine are found, but when a whole region is buried in ice there can of course be no surface moraines, and the transport of detritus must be confined to the sole or base of the ice-sheet, and to the sub-current rivers. With

[1] "Geol. Mag." Dec. 2, vol. iii. p. 18.

respect to the capacity of such ice-sheets for transport and erosion we know very little at present from actual observation, but as regards erosion, it may be safely asserted that if any part of a valley glacier exercises erosive power, those parts of an ice-sheet which move down buried valleys must have a more powerful erosive action.

It is believed that, at the period when the Swiss glaciers attained their greatest development and extension, North Britain and Scandinavia were covered by ice-sheets which moved out in every direction from the main lines of watershed, which were then great gathering grounds of snow. The smoothened and rounded outlines of the lower hills in these countries, and the scratched and polished surfaces of the rocks on their sides, are generally attributed to the rasping and grinding action of these enormous masses of ice.

CHAPTER X.

MARINE AGENCIES.

ACTION of Waves.—The upper surface of the sea is kept in continual agitation by the force of the winds, which raise it into waves of all dimensions; these waves roll in upon every exposed coast-line throughout the world, and act as instruments of erosion and destruction. To estimate the power of sea-waves, they must be seen under the influence of a storm or gale of wind. Just as a brook in time of drought furnishes no measure of the work it does in time of flood, so the sea on a calm day gives no idea of the force with which storm waves can break on a rocky shore.

It has been ascertained that the average force of the breakers in winter time on the west coast of Scotland is equal to a pressure of 2,086 lbs. (nearly a ton) on every square foot of rock; during a storm it is greater. Mr. Stevenson found by experiments at the Bell Rock Lighthouse that the pressure was sometimes a ton and a half upon the square foot. and that at Skerryvore in the Atlantic it was doubly powerful, viz., about three tons to the square foot.

Such a force is evidently capable of dislodging and moving very large fragments of rock, especially if the blocks have been previously loosened by the action of rain and frost. Sir Arch. Geikie[1] states that on the coast of the Pentland Firth blocks from 7 to 13 tons in weight had been quarried out of the cliffs at a height of 70 feet above the sea; the waves must have risen to that height, and still have been able to bring down these immense frag-

[1] "Scenery and Geology of Scotland," p. 61.

ments. In other places they have torn up similar masses of rock, and heaped them together at a height of 62 feet.

The damage and destruction which is often wrought upon piers and breakwaters during storms enables us to realize the enormous power of the waves, and anyone who has witnessed the making of a breach in such massive masonry will be better able to appreciate the action of the sea upon coasts and cliffs. During heavy gales at Plymouth in 1824 and 1829, blocks of limestone and granite, weighing from to two to five tons, were washed about at the breakwater like pebbles. About 800 tons of such blocks were borne a distance of 200 feet up the inclined plane of the breakwater. In one place a block of limestone, seven tons in weight, was washed a distance of 150 feet.[1] On the coast of Clare, in Ireland, blocks of rock may be seen which have been torn from rock-masses 20 feet above high-water mark, and thrown up on to the grass full 20 feet higher and 20 yards farther back.[2]

The mere blow and force of the wave, however, is not the whole of the force exercised; when the water is dashed against a rock or cliff, some of it is injected into every crack and crevice it can find, and its pressure is exerted in forcing asunder the walls of the fissure. Moreover the air that was previously in the fissures is suddenly compressed and impelled into the minuter cracks and planes of division. With the recess of the wave the pressure is suddenly relieved, and the air and water rush out with a suction that is capable of loosening and dislodging large blocks of rock. No sooner are such fragments torn away from the cliff than they are immediately converted into engines of further destruction, for they are lifted by the waves and hurled against the rocks, so as to act like hammers or battering rams.

To sum up, therefore, it may be said that when sea-waves break full against the face of a cliff, four different physical processes are set in action, all of which assist in the work of destruction: these processes are:—

1. The force and impact of the waves.

[1] De la Beche's "Geological Observer," p. 47.
[2] Jukes' "Manual of Geology," second edition, p. 220.

2. The hydraulic pressure of the water in the larger fissures.
3. The alternate compression and expansion of air in the cracks of the rock.
4. The employment of stones and boulders as battering-rams.

Formation of Caves, Coves, and Inlets.—If the larger cracks and fissures run at right angles to the cliff, they form so many lines of weakness, which yield more readily to the continued action of the waves, and a long cave or else an open inlet is gradually formed. In other cases the larger cracks or master joints run parallel to the face of the cliff; shorter and wider cavities are then formed near the base of the cliff, which is thus undermined till one of the main joints is reached, when the unsupported mass above falls in ruin on the shore. The breakers then proceed to reduce the size of the fallen fragments, dashing them one against the other, and breaking them up into pebbles and sand, till at last they are washed away, and the face of the cliff is exposed again to fresh assaults.

Instances of the action of the breakers on jointed rocks are to be seen on all coasts. On the western coasts of Europe the severest storms and strongest gales come from the westward, with winds ranging from S.W. to N.W., and as they sweep over the vast expanse of the Atlantic Ocean they raise up enormous waves which break upon the land with tremendous force. The hard rocks of the western coast of Ireland afford many illustrative examples of the action of these breakers as going on at present, their cliffs, caves, and rocky islets having been formed by inroads. Mr. Jukes states, on the authority of Mr. W. L. Willson, late of the Geological Survey of Ireland, that in the far part of the promontory between Bantry and Dunmanus Bays there are dark holes in the fields some distance back from the edge of the cliffs, looking down into which the sea might be dimly seen washing backwards and forwards in the narrow cavern below.

"At high water, and during gales of wind, with heavy breakers rolling in upon the coast, vast volumes of water are poured suddenly into these narrow caverns, and rolling on, compress the air at their further end into every joint

and pore of the rock above, and then, suddenly receding, suck both air and water back again with such force as now and then to loosen some part of the roof. Working in this way, the sea sometimes gradually forms a passage for itself to the surface above, and if that be not too lofty, forms a 'blow-hole,' or 'puffing-hole,' through which spouts of foam and spray are occasionally ejected high into the air."[1]

Some of these blow-holes open down into cavernous gullies, which lead from one cove to another, behind bold headlands of even a hundred or more feet in height; showing the commencement of the process by which headlands are converted in islands. One such square precipitous island, near Loop Head, County Clare—which in 1862 was

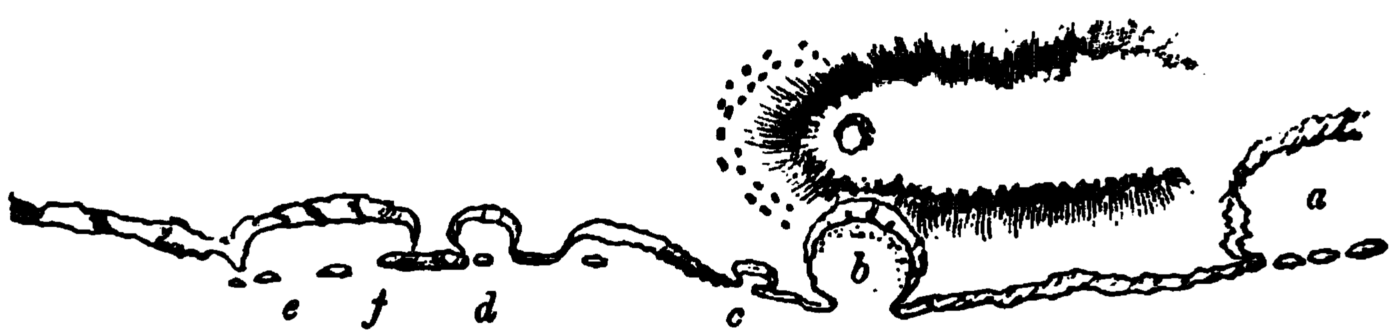

Fig. 44. Part of the Dorsetshire Coast (distance about five miles). *a*, Mupe Cove. *b*, Lulworth Cove. *c*, Stare Cove. *d*, Man-of-War Cove. *e*, Durdle Cove. *f*, Barn Door.

at least 20 yards from the mainland—was said by the farmer who held the ground to have been accessible by a twelve-foot plank when he was a boy.

Another cause of the irregularities of a coast-line is to be found in the unequal hardness or resistant power of the rocks themselves. The more yielding strata are worn into deep bays and inlets, while the harder rocks stand out as capes, promontories, and detached islets.

Nowhere is this result so clearly seen as on the south-west coast of Ireland, where beds of indurated sandstone form the bold headlands separating Dingle, Kenmare, Bantry, and Dunmanus Bays, while these inlets are all eroded out of more destructible shales and limestones.

The coasts of Devon and Cornwall present similar

[1] Jukes' "Manual of Geology," second edition, p. 220.

examples on a smaller scale, the numerous creeks and coves being all scooped out of some comparatively soft rock, frequently the shaly slate locally known as *killas*, while the harder rocks, such as granite and dolerite, have offered more resistance to the breakers and stand out as headlands and promontories. Polventon Cove, on the east side of Trevose Head, is a natural harbour formed in this way, and protected from the north-west winds by a jutting ridge of hard, igneous rock (greenstone), which forms an efficient breakwater.[1] The erosion of the shores of Tor Bay has been described by Mr. Pengelly.[2]

In England, however, the most remarkable instances of this selective action of the waves are to be found on the Dorsetshire coast. The cliffs which form this coast consist of a variety of strata, some of which are very much softer and more yielding than the rest. As a consequence, wherever these are brought within the reach of the waves deep recesses, or coves, have been excavated out of them. No less than six of these coves occur within the distance of five miles, while the intervening portions of the coast-line form nearly straight ranges of cliffs. These features are shown in plan in fig. 44, and an idea of the scenery they produce may be obtained from the view of Durdle Cove in fig. 45; the eastern cape of this bay is formed by a projecting crag of hard limestone (Portland stone), through which the waves have worn a wide gap or archway known as the "Barn-door." The western cape consists of chalk, while the inner cliffs consist chiefly of sands and clays, to the presence of which the bay owes its existence.

The Isle of Wight owes its lozenge shape entirely to the relative hardness of the rocks of which it is composed. Through the middle of the island runs a high ridge of chalk, the two ends of which project east and west, and form the promontories known respectively as Culver Point and The Needles (see fig. 46, borrowed from Mantell's "Excursions"). The Culver cliffs are flanked by Sandown and Whitecliff Bays, while Brixton and Alum Bays occupy the same position with regard to the Needles. All these

[1] See De la Beche's "Geological Observer," p. 51.
[2] "Geologist," vol. iv. p. 447.

Fig. 45. Durdle Cove, seen from the east end. (From Mantell's "Geological Excursions.")

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the sea is comparatively quiet. Between these points, therefore, a line is reached where the erosive and accumulative actions balance one another, and below which little erosion takes place. This line is always a little above the level of low tide, and may be called the *line of least erosion.*

During storms, however, the power of the waves is still great even at low tide, and they disturb the bottom to some depth below the low water level, as is testified by the shells, stones, and seaweeds torn from their habitat below low water mark and cast up on the beach after storms. During violent gales it is said that the sea-floor has been disturbed to a depth of 50 fathoms, but such disturbance would only cause an oscillation of the sand and mud at the bottom.

On a rocky shore the tendency of these conditions is to

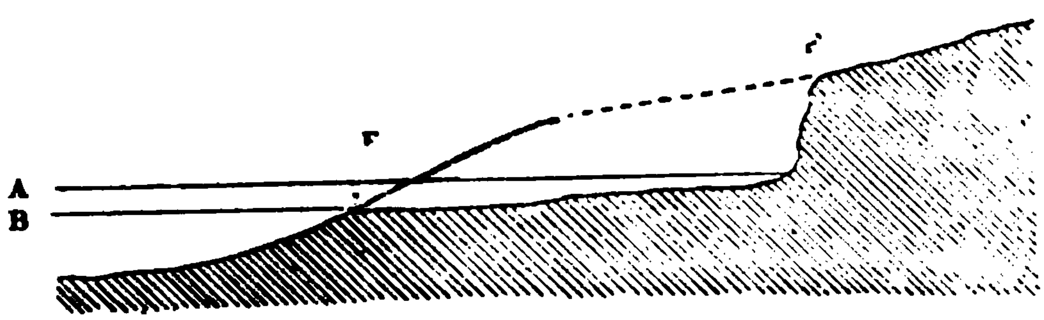

Fig. 47. Formation of a Shore Platform.

produce a horizontal or gently sloping platform, the outer edge of which corresponds to the line of non-erosion, so that its surface is bare at low water. This platform is often called a *scar*, and its inner side is bounded by cliffs more or less lofty, according to the height of the land which is eaten into. Fig. 47 is a section across such a platform, the line A representing high tide level, and B low tide level. When the land was first brought into the position with regard to the sea-level which it is supposed to occupy in fig. 47, no cliffs existed, but the line E F was a continuous slope. The sea began to cut into the land at the point E, and the formation of the platform has been effected by the recession of the cliffs to the point F.

The rapidity of Marine Erosion.—The rate at which cliffs are being worn back depends on various circumstances, partly on the position of the cliff and depth of water at

its base, partly on the force of the breakers, partly on the hardness of the rocks composing the cliff, and partly on the assistance derived from sub-aërial agencies—rain, frost, and springs—which generally work faster than the waves, and cause the cliffs to slope backward at a greater or less angle from the shore.

The most important condition is the hardness or resistant power of the rocks themselves. Where the rocks of the coast are hard and massive little change is noticed in the course of a century, but where the whole coast consists of the softer kinds of rocks, and especially if it is swept by a strong current which can readily carry off the eroded materials, the waste of land is sometimes very rapid, so that all the inhabitants become sensible of it. This is the case for long distances on the eastern and southern coasts of England, and even within the last few centuries the destruction of land has been so great, that the sites of many villages and some considerable towns along the coasts of Yorkshire, Norfolk, Suffolk, Essex, and Kent, are now beneath the sea, which has eaten away the ground on which they once stood. It should be observed, however, that it is only at certain points along these coasts that destruction is going on, not along their whole extent. At some places, as will hereafter be mentioned, deposition and accretion are taking place. For the facts which follow, my authority, when another is not specially cited, is the tenth edition of Lyell's "Principles of Geology."

In Yorkshire the waste is most rapid along the coast of Holderness, between Flamborough Head and Spurn Point, at the entrance of the Humber; this tract consists of beds of clay, gravel, and sand, which form low cliffs against which the waves beat, while a strong current sets from the north and carries away the débris.

"For many years," says Professor Phillips, "the rate at which the cliffs recede from Bridlington to Spurn, a distance of 36 miles, has been found by measurement to equal on an average 2¼ yards annually, which upon 36 miles of coast would amount to about 30 acres a year. At this rate the coast, the mean height of which above the sea is about 40 feet, has lost one mile in breadth since the Norman Conquest, and more than two miles since

the occupation of York by the Romans." In some places the loss of land is said to be as much as 5 yards per annum.[1]

The sites of the villages of Auburn, Hartburn, Hyde, and Ravenspur, are now sand-banks dry only at low water, though Ravenspur, where Bolingbroke landed to depose Richard II., was once so large and flourishing a sea-port as to be a rival of Hull.

Norfolk.—The site of the old town of Cromer is now in the German Ocean, the inhabitants having continually built inland as the sea gained on them. It is stated by Mr. Redman[2] that during the twenty-three years which elapsed between the Ordnance Survey of 1838 and the year 1861, a portion of the cliff composed of sand and clay between Cromer and Mundesley receded 330 feet, amounting to a mean annual waste of 14 feet; these cliffs are from 200 to 250 feet high, and the amount of material carried away from them every year must, therefore, be enormous. The facts given by the same authority show that along the cliffs between Mundesley and Happisburgh the average annual rate of waste is about three yards. This waste is largely due to the work of rain and springs, for the cliffs often founder down in a series of landslips; but this movement would soon cease if it were not for the removal of the talus by the action of the sea.

On the same coast churches, villages, and manors, such as those of Shipden, Wimpwell, and Eccles, have one after another disappeared, so that their previous existence is only known from old records.

Suffolk has suffered in a similar manner. Dunwich, now only an inconsiderable village, was once the chief port in the county. It is stated in Doomsday Book that two tracts of land outside the village had been taxed by Edward the Confessor, but had been destroyed in the few years which had elapsed between that time and the Conqueror's Survey. In other later records mention is made of, at one time, a monastery, at another several

[1] See a paper "On the Encroachments of the Sea from Spurn Point to Flamborough Head," by R. Pickwell, "Proc. Inst. Civ. Eng." vol. li. p. 191.

[2] "Proc. Inst. Civ. Eng." vol. xxiii. p. 31.

churches, then the old port, then 400 houses at once, and gradually the gaol, the town-hall, the high roads, then of ancient cemeteries, the coffins of which were for some time exposed in the cliff—all swept away by the devouring sea. The waste of Dunwich cliff has ceased for some years, and shingle now accumulates at its base; but the neighbouring cliffs of Easton Bavent and Covehithe are receding at the rate of from 20 to 30 feet in a year.[1]

Beacon Cliff, near Harwich, has wasted at a very rapid rate; it is about 50 feet high, and consists entirely of clay. Captain Washington ascertained that between the years 1709 and 1756 it had receded a distance of 40 feet; between 1756 and 1804, 80 feet had been swept away, and between 1804 and 1841, no less than 350 feet, showing a rapidly accelerated rate of destruction.

Kent.—The Isle of Sheppey, off the north coast, furnishes another example of the rapid destruction of clay cliffs, which are continually foundering down under the combined attacks of rain-water and sea-waves. An account of the landslips constantly taking place along the north coast of this island has already been given (p. 121), and the sea is chiefly employed in washing away the ruins which fall on the shore. As much as 50 acres of land have been lost in 20 years, and if the present rate of destruction should continue, it is easy to foresee the total destruction of the island.

Still farther east stands the church of Reculver, upon a low cliff of clay and sand; Reculver was a Roman station, and even in Henry VIII.'s time the church was nearly a mile from the sea. The Roman camp was destroyed in 1780, and part of the churchyard in 1804, but, since then, artificial means have been taken to break the force of the waves and to preserve the church as a landmark.[2]

Sussex.—Westward of Hastings there has been much loss of land, and though Pevensey Level, with its border of shingle, has been formed in historical times, yet for more than a century the whole shore-line has been giving way, the rate of waste now being between 3 and 7 feet per

[1] See "The Geology of Southwold," by W. Whitaker, Mem. Geol. Surv. 1887.
[2] See Lyell's "Principles," vol. i. p. 523.

annum. At Langney Point between the years 1736 (Desmarest's Survey) and 1844 (Ordnance Survey) the sea had advanced more than half a mile. A comparison between the two Surveys above mentioned shows that the coast between Eastbourne and Beachy Head has receded to the extent of more than a quarter of a mile, and in some places as much as 600 yards, the average loss being between 12 and 15 feet per annum[1] (see map, fig. 48). Of the martello towers constructed here in 1806, four (Nos. 69 to 72) have since been destroyed by the encroachments of the sea, and are now below highwater mark.

At Beachy Head, which is a promontory of hard chalk, the erosion is less rapid, but falls from the cliff are frequent, and the largest landslip of which record remains took place in 1813, when a mass of chalk 300 feet long and about 80 feet wide was precipitated on to the shore.[2] Seven towers of chalk called the Seven Charles formerly stood out from these cliffs, but the last of them, which was known to have withstood the attacks of the sea for more than a century, fell in 1853.[3]

Between Newhaven and Brighton the average rate of waste is 3 feet per annum, and Mr. H. Willett states that at Aldrington (3 miles west of Brighton) the encroachment of the sea amounted to 270 feet in ten years, or an annual rate of 9 yards, these figures being obtained by actual admeasurement.

The promontory known as Selsey Bill has likewise suffered great loss. In the time of the historian Bede, A.D. 731, Selsey was a peninsula, and contained 5,220 acres of land; at the present time its area only amounts to 2,880 acres. It was for many years a Bishop's see, and possessed a cathedral and episcopal palace with a large park, which in the time of Henry VIII. was well stocked with deer. Now the site of these buildings is said to be about a mile from the coast, and a small plot called Park Coppice is the only remnant of the park; though the shore and sands

[1] Redman, "Proc. Inst. Civil Engineers," vol. xxiii. For the use of this illustration (fig. 48) I am indebted to Rev. H. E. Maddock and Mr. Chambers, of Eastbourne.

[2] Webster, "Trans. Geol. Soc." vol. ii. p. 191.

[3] Chambers' "Guide to Eastbourne."

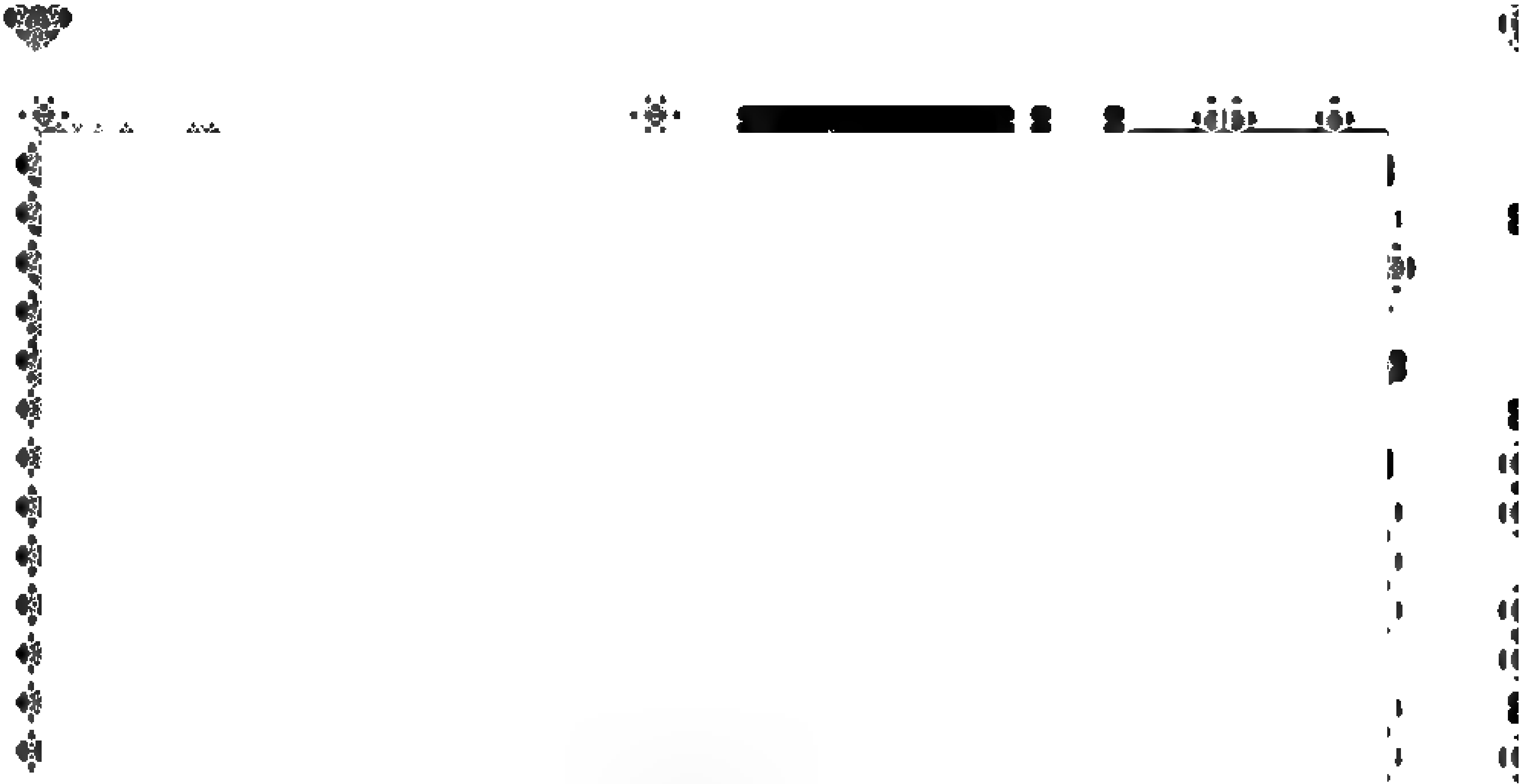

Fig. 48. Changes in the coast-line between Beachy Head and Pevensey. The shaded parts are land, the lined portion consisting of sand and shingle. The numbers indicate martello towers. Scale about one mile to an inch.

are still known locally by the name of the "Bishop's Park."

Hampshire.—The cliffs between Hurst Shingle Bar and Christchurch are likewise worn back at a rapid rate, the destruction being estimated at a yard per annum. Christchurch Head stands out as a promontory, and it is a noteworthy and significant fact that this is the only point between Lymington and Poole Harbour in Dorsetshire where any hard stony masses occur in the cliffs. "Five layers of large ferruginous concretions," says Lyell, "somewhat like the septaria of the London Clay, have occasioned a resistance at this point, to which we may ascribe this headland."[1]

The configuration of the Isle of Wight, and the extent to which it has suffered from marine erosion, have already been mentioned (see p. 168).

Dorsetshire.—The same phenomena are repeated in the districts of Purbeck and Portland. The manner in which the coves of the Purbeck coast have been formed has already been mentioned; at Portland the erosion has been much more considerable: the cliffs here consist of a soft, shaly clay, overlaid by a massive limestone; the clay is rapidly excavated, so that the cliffs are undermined, and large masses of the superstratum then fall by their own weight. The action of the waves is assisted by that of the springs thrown out beneath the limestone, as in the Isle of Wight, p. 123. Large landslips have often occurred, notably one in 1792, when a tract of ground a mile and a quarter long and 600 yards broad was moved towards the sea. The isle of Portland is, in fact, the last remnant of a once extensive tract of land.

Similar destruction and loss of land is going on along the coast between Bridport and Axmouth, the great landslip near the latter place having been already mentioned (p. 124). Near Lyme Regis the rate of waste has been estimated at about three feet per annum.

Erosion of Heligoland.—The destruction of land which can be accomplished by the sea under certain circumstances will be better realized if we take the case of a

[1] "Principles of Geology," tenth edition, vol. i. p. 533.

[illegible] n island in [illegible] olstein. It [illegible] orm the east

[illegible] 0 miles to an [illegible] of the island [illegible] e area shaded [illegible] , when it was [illegible] ded areas are [illegible] r being then

Fig. 50. A Bird's-eye View of Heligoland from the south-east.

of England. No accurate description exists of its size in very early times, but it is known to have been continually diminished by incursions of the sea during high tides and storms. Fig. 49 is a reduced copy of a map said to have been "copied from an old map in possession of the Governor of Heligoland," and showing the area of the island at three different periods.

The outlines here shown may not be strictly accurate, and the area represented as existing in A.D. 300 may possibly be rather too large,[1] but the map may be taken to show the approximate size and the relative position of the portions destroyed between the dates mentioned. It is very probable that the larger part of the island, as it existed in A.D. 800, was low and flat, hence the great loss of land between that date and 1300. There can be little doubt that the portion now remaining has survived because it was the highest and firmest part of the island. It is now about a mile long and two furlongs broad at its widest part, with cliffs 170 feet high (see fig. 50). About half a mile eastward is Sandy Island, which was united to the main island by a ridge of chalk till as late as 1720, but having been largely quarried by the inhabitants, it was demolished by the sea in that year. The island shown in fig. 49 as existing in 1649, still further to the east, is now the Lorelei Bank, and covered by four fathoms of water.

Reference to the Admiralty Chart shows that north-east of the present island are long reef-like banks, large parts of which are only just covered at low tide. These banks have a N.W. and S.E. direction parallel to that of the rocky scars around Heligoland, and their surface is partly bare rock and partly stones. A bottom of rock and stones is frequent all over the area encircled by the 10 fathom contour line, an area which measures 5 miles from north to south, and about 3½ from west to east, and is united by a narrow neck to the shallow ground on the east, of which the Lorelei Bank is a part. These facts are sufficient to show that the old map is to a large extent

[1] This map, with a note by Mr. W. H. Penning, was published in the "Geol. Mag.," 1876, Dec. 2, vol. iii. p. 283, and I am indebted to the editor for the use of the block.

confirmed by the features of the sea-floor around the present island.

Action of Tidal Currents.—The consideration of tidal currents has been rather neglected by geologists, and it is very difficult to form an adequate conception of their action because the process is hidden from ordinary observation. Some facts have been recorded, however, which seem to indicate that these currents exercise a certain amount of erosive action on the sea-floor, more particularly where they pass between islands, or round headlands.

The height of the tide, and the force of the currents it produces, depend upon the configuration of the coast-line. In the open ocean it is merely a slight lifting of the surface, but the rotation of the earth converts this into a long low wave, the movement and mass of which become appreciable as it approaches the land. At the headlands, which are first reached by the tidal wave, the rise of water is seldom more than six feet, but where shelving shores and narrow gulfs or bays confine the tidal waters into a narrower space, the rise and fall of water often amounts to 30 or 40 feet. In the Bristol Channel, for instance, it is more than 40 feet, and the currents produced are proportionately powerful.

Where islands occur which present a considerable length of coast to the advance of the tidal wave, this is divided into two portions, which travel round the island in opposite directions, and the configuration of the main coast beyond the island may cause the one portion of the wave to rise to a higher level than the other portion. In such circumstances a strong current or *race* will be developed in the channel between the island and the mainland. Such races are common among the islands off the west coast of Scotland, and where the channels are narrow counter currents are often set up with dangerous eddies and whirlpools. The famous Maelstrom or Whirlpool of the Lofoten Islands of Norway is due to this cause, as are also the currents of Hellgate in the narrow channel between New York Bay and Long Island Sound. "If the waters of the sound could be separated from those of the bay by a partition at this point, the water at high tide on the

sound side would stand five feet higher, and at low tide five feet lower, than the water on the bay side."[1]

It is a mistake to suppose that tidal currents are merely surface streams, they affect the whole body of water in the channel or bay, and in some cases the velocity of the current at the bottom is greater than that at the surface. In the Little Minch off the west coast of Scotland, between Glas Island and Sgeir-i-Noe, the flood-stream often takes long fishing-lines down to the bottom. "It is a remarkable circumstance, indicative of the great depth of the tidal stream here, that the buoys, though anchored in 70 or 80 fathoms, are taken completely to the bottom, star-fish and other marine animals being found attached to them."[2] As in fine weather the surface velocity here is only $1\frac{1}{2}$ knots per hour, it is evident the bottom velocity must be greater. In the Gulf of Coirebhrecain, between Scarba and Jura, there is a dangerous race where the tide runs with a velocity of $9\frac{1}{2}$ miles an hour, causing eddies and counter currents along each side of the gulf, which has a maximum depth of 80 to 100 fathoms; and Mr. Reade remarks that the greatest depth occurs just in the position it should do if it were due to the excavating power of the current.

In this gulf, and in some other *deeps* off the Scottish coast, bare rock is marked on the Admiralty charts, while all around is mud or sand, and Mr. Reade (*loc. cit.*) thinks it possible that most of these valley-like hollows have been excavated by the action of the tidal currents, for though their erosive influence on a rocky bottom may be small, on a soft bottom it may be great, and such a current may have scooped away the sand and clay which filled the hollow till it reached the rock below. By others these deeps are regarded as submerged portions of ancient valleys and lakes, but there is much to be said for Mr. Reade's view.

Tidal currents certainly seem to have more erosive power than they are generally credited with, for it is otherwise difficult to account for the depth of water out-

[1] Hinman's "Physical Geography," 1890, p. 130.

[2] "Sailing Directions for West Coast of Scotland," p. 119, quoted by M. Reade in "Phil. Mag.," 1888, p. 339.

side coasts which are known to have been receding at the rate of several yards a year. Thus Lyell records that in one part of Sherringham harbour, on the Norfolk coast, there was in 1829 a depth of 20 feet of water where forty-eight years before there stood a cliff 50 feet high. Now if the waves were the only agent of erosion, the tract over which they had advanced would have been a shallow flat, and would not have been eroded to such a depth. Mr. Clement Reid has recognized this consideration, and adds a remarkable instance of submarine erosion which came under his personal notice while surveying the Norfolk coast. This was the deepening and scouring out of a submarine channel during a storm to a depth of 15 fathoms, and the tearing off of slabs of ironstone from the rocky side of this channel at a depth of at least 10 fathoms, these slabs being cast up on the beach.[1]

Bottom currents appear to exist even in the open ocean and at considerable depths. Thus Mr. Stallibrass records the existence of strong currents at a depth of 1,000 fathoms between the Canary Islands, and says their scouring action may be clearly detected. Mr. J. Y. Buchanan also remarks: "If we find hard ground, we know that there must be something to prevent the accumulation of sediment. Now the only thing that prevents this is a current; and one help that telegraph soundings have given to geographical science is, the indication that tidal currents exist even at very great depths in the open sea."[2]

It has lately been pointed out that in early geological times the rise and fall of the tides was in all probability much greater than it is at present. The moon has been gradually increasing its distance from the earth, and when it was much nearer, its tide-producing power will have been greater; and greater tides would enable the waves to act over a greater vertical space. Hence Mr. G. H. Darwin and Dr. Ball[3] conclude that marine erosion must formerly have proceeded at a much more rapid rate than at present,

[1] "Geology of the Country round Cromer," Mem. Geol. Survey, 1882, pp. 43, 130.

[2] "Journ. Soc. Tel. Engineers," 1887, p. 509.

[3] G. H. Darwin, "Phil. Trans.," 1879, and Dr. Ball in "Nature," vol. xxvii. p. 201.

but it is by no means certain that such a conclusion is warranted by the facts. We have seen that marine erosion is only very rapid in certain cases where the waves at high tide beat against the foot of a line of cliffs, and that even in such cases the rate of waste depends greatly on other circumstances, such as the hardness of the rocks, the existence of springs, and the work of rain and frost. Wherever there is a beach below the cliffs, the waves are engaged in hammering this beach and grinding its pebbles into sand during the greater portion of the time between high tides.

Consequently a greater rise and fall of the tide would not do much toward accelerating the waste of the land, though it would doubtless create stronger currents, and so somewhat increase the amount of submarine erosion in certain localities.

If great tides mean great erosion, then we ought to find some evidence of such a result at those places where great tides now exist. The Bay of Fundy (where the tide rises 60 feet) and the Bristol Channel (where it rises 40 feet) are such places, but their shores do not show any signs of excessively violent or rapid erosion. Cliffs exist in both cases at about high-water mark, and below them lies a long stretch of gradually sloping beach.

The recession of these cliffs is no doubt great in some places, but no one has yet suggested that it is more rapid than at other places where rocks of a similar kind are exposed to marine erosion.

Coast-ice.—In high latitudes where the shallow water along the coasts is frozen every winter, a particular form of ice comes into play, and constitutes an erosive and detritive agency of no mean importance. During the winter a thick and often broad shelf of ice is gradually formed along the shore, its thickness increasing with every tide, until it sometimes reaches a height of 30 or 40 feet, and its seaward face presents the appearance of a bold wall of ice.

When spring comes, landslips occur, and tons of stones and rock-fragments, loosened by the winter's frost, fall upon the surface of the *ice-foot*, as this shelf is often called. Moreover, the blocks, stones, and shingle which rest on the shore beneath are frozen into the bottom of the ice

and become part of its mass. The coast-ice is thus charged with a load of stones and boulders both on its upper and lower surfaces, just in the same way as glacier-ice is, only the quantity of débris is probably greater.

As the thaw proceeds in summer time, this ice-foot is broken up by the waves, and large masses are driven on to the shore during storms, crushing and grinding the rocks over which they are pushed; other portions are separated from the coast and floated out to sea, forming great rafts or *floes*, each with its load of rock débris.

Even in calmer weather it is clear that coast-ice, having numerous fragments of rock fixed in it, and being borne backwards and forwards by the tide, must exercise an enormous grinding and grooving action. Both the stones themselves and the surfaces over which they are moved will be scratched and abraded, and much mud will be produced by the process. It may be observed, also, that a stone fixed in the ice-foot, and scratched along one side by contact with the rock below, may be dropped when the ice begins to thaw, and afterwards ground along its other sides by the stones still fixed in the ice above, so that it may eventually bear scratches all over it, as is the case with so many stones in our Boulder clays.

Speaking of ice-action on the coasts of Grinnell Land, part of North Greenland, Messrs. Fielden and De Rance make the following observations:[1]—"Sea-ice driven on shore by gales, or moving up and down with the tides, is a very potent factor in glaciating rocks and pebbles. Along the shores of the Polar basin this process of glaciating was seen in progress by one of us; and he records in his 'Journal' that at the south end of a small island in Blackcliff Bay (lat. 82° 30 N.), the bottom of the ice hummocks, some 8 to 15 feet thick, were studded with hard limestone pebbles, which were rounded and scratched as distinctly as others taken from moraines; when extracted from the ice, only the exposed surfaces, as a rule, were glaciated. As the tide recedes the hummocks do not always arrive at a position of rest without some disturbances of the subjacent material, particularly on a shelving

[1] "Quart. Journ. Geol. Soc.," vol. xxxiv. p. 566.

shore, and the sliding of the hummock to a lower level, and the sound following on the grating together of the pebbles beneath may be noted. In many places where gaps occurred in the lines of ancient sea-terraces, the basement rock, as well as some of the pebbles in the terraces, were found to be glaciated, and there can be no doubt that this is due to the action of shore-ice, the condition of the terraces precluding the idea that it might have been the result of glacier action."

An illustration of the action of such ice on a shelving shore in a much lower latitude is mentioned by Dr. Forchhammer,[1] who states that during a hard frost in February, 1844, sheets of ice were formed in the Sound between Sweden and Zealand, and some of these were driven by a storm into the Bay of Tăarbejik, and forced up on the beach, forming a mound more than 16 feet high. When he visited the spot next day, he saw "ridges of ice, sand, and pebbles, not only on the shore, but extending far out into the bottom of the sea, showing how greatly its bed had been changed, and how easily, where it is composed of rock, it may be furrowed and streaked by stones firmly fixed in the moving ice."

To the action of such masses, but still more to that of ground-ice which forms on shallow bottoms, and contains stones frozen into its under surface, Professor Forchhammer attributes the striation of the rocky surfaces round the shores of the Baltic.

When to the ordinary action of tides and winds is added the impact of some of the large masses of ice, which are set loose from the Arctic regions in summer time, and are often driven on to the more southern coasts, still greater results are produced. The action of this pack-ice on a shelving shore is thus described by Professor Milne:[2]— "When we reflect upon the immense mass in one of these moving fields of ice, we can hardly conceive the energy that is stored within it. Everything has to give way before it; and the coast-ice, with its set of gravers firmly bedded in its base, is pushed high and dry, sometimes as much as

[1] "Bull. Soc. Géol. de France, 1847," tom iv. p. 1182.
[2] "Geological Magazine," Dec. 2, vol. iii. p. 405.

100 yards back from high-water mark. It is in this way, by the coming-in of the northern pack, the rise and fall of the tide, and other causes, that the land-ice is driven ashore, and many of the scratches and grooves so common round the coast of Newfoundland have been made."

Sir George Nares observed that in some places on the coast of Grinnell Land huge floe-bergs and ice-blocks had been forced up on the inclined shore, until a rampart-like barrier of solid ice-blocks was accumulated, measuring about 200 yards in breadth, and rising 50 feet high.[1]

The impact of this floe-ice seems also to have a rounding and moulding effect upon such islands and prominences of rock as are exposed to its force, producing forms which, on a large scale, resemble the *roches-moutonnées* formed by glaciers. Professor Milne instances a small islet called Funk Island, near Newfoundland, which is situated directly in the course of the ice-floes coming southward from Baffin's Bay and Labrador. "The northern end of this island, which has every year to face the pressure of the vast fields of ice which are borne down upon it, is visibly worn down, and covered with erratic boulders, whilst the opposite extremity is a low but abrupt cliff."

He argues, therefore, that much of the stratching and modelling which has hitherto been referred to the action of enormous glaciers, may have been produced by the agency of coast-ice and floe-ice acting on the surface of the country during its last slow emergence from the sea.

The part taken by these ice-floes in transporting and depositing material will be described on a future page.

[1] "Voyage to the Polar Sea," vol. i. p. 276.

SECTION II. (continued).

B. *Processes of Reconstruction.*

CHAPTER XI.

AT the commencement of Section II. it was stated that in considering the agencies concerned in the continual detrition and renewal of the earth's surface, we should first describe their destructive and dispersive effects, reserving all mention of their reconstructive effects to a future section. Accordingly we now proceed to give some account of the manner in which new deposits are formed out of the materials obtained by the several agencies already described, and to indicate the nature of the formations thus produced. These may be divided into four classes, according to the conditions under which they have been accumulated, each except the second being subdivided into three groups according as they owe their formation to mechanical agencies, to chemical action, or the growth of organic matter. The deposits formed by rivers and glaciers, however, are all the result of mechanical action.

This classification is set out in the following table:—

Terrestrial	Rain, frost, and wind .	Mechanical.
	Springs and percolating water	Chemical.
	Worms and plants . .	Organic.
Fluviatile	Rivers	Mechanical.
	Glaciers	
Lacustrine	Subsiding sediment . .	Mechanical.
	Evaporation of water . .	Chemical.
	Animal agency	Organic.
	Vegetable agency . . .	

Marine	Subsiding sediment . .	} Mechanical.	
	Action of sea-ice . . .		
	Evaporation of water .	Chemical.	
	Animal agency	Organic.	

TERRESTRIAL DEPOSITS.

§ 1.—*Mechanically formed.*

1. **Soil and Rain-wash.**—It was shown in Chapter VI. that the heat of the sun, the fall of rain, and the freezing of water exercise a powerful effect upon the surface of all rocks at or near the surface of the earth, and lead to their gradual decay and disintegration.

In temperate and humid climates rain is by far the most potent of these agencies; acting in the first placo chemically by means of the acids and oxygen which it contains, it decomposes and dissolves some of the constituents of the rocks exposed to its influence, and so loosens the coherence of their constituent particles that they are rendered soft and crumbling to a greater or less depth from the surface. This rotten and decomposed portion of the rock is then subjected to still further disintegration by the mechanical action of the falling drops of rain, and the lighter particles are eventually washed away by the rills into which the rain-drops collect, while the residue remains to form the soil of the district.

The various kinds of soil which mantle the earth's surface, and conceal the underlying rock or subsoil, have been primarily produced in this way, the formative action being assisted, as we shall presently see, by the agency of plants and earth-worms. The nature of the soil, therefore, depends largely upon the character of the rock beneath, and is heavy or light according as argillaceous or arenaceous matter preponderates in the rock from which it has been formed. Its quantity, too, depends partly on the kind of rock acted upon, its capacity or incapacity of resisting disintegrating agents, and partly upon the contour and slope of the ground.

It has been ascertained that the soil has everywhere a

tendency to descend from higher to lower levels: wherever there is a slope the soil is bodily but slowly travelling from the top to the bottom, and the steeper the slope the more rapid is the motion; so that in valleys and *bottoms* where it is not carried away by streams, considerable deposits of *rain-wash* are gradually accumulated. If a trench is cut down the side of one of our English valleys, it will be found that on the upper slopes the soil is thin, and the subsoil may perhaps be within six inches of the surface, while lower down it will be concealed by 5 or 6 feet of accumulated rain-wash. In some valleys such rain-wash is thick enough to be dug for brick-earth. In other places rain-wash consists of loamy sand or even fine gravel.

Dr. Darwin made some interesting experiments with the view of estimating the average rate at which the soil moves,[1] and he found that on a grass-covered slope with an inclination of $9\frac{1}{2}$ degrees, 2·4 cubic inches of earth (weighing 1·85 oz. whilst damp), annually crossed a line measuring one yard in length. "This amount," as he says, "is small, but we should bear in mind how many branching valleys intersect most countries, the whole length of which must be very great, and that earth is steadily travelling down both turf-covered sides of each valley. For every 100 yards in length in a valley with sides sloping as in the foregoing cases, 480 cubic inches of damp earth, weighing above 23 lbs., will annually reach the bottom. Here a thick bed of alluvium will accumulate, ready to be washed away in the course of centuries, as the stream in the middle meanders from side to side."

On steeper slopes the motion of the soil-cap is much more rapid, and in humid climates it sometimes becomes very obvious. Thus Dr. Coppinger observes:—"The most characteristic feature in the scenery of the western shores of Patagonia is owing to the phenomenon of 'soil motion,' an occurrence which is here in a great measure due to the exceptionally wet nature of the climate. This slippage of the soil-cap seems in this region to be continually taking place wherever the basement rock presents a moderately inclined surface. . . . The soil-cap takes with it in its

[1] "Vegetable Mould and Earth Worms," 1881, p. 269.

downward progress not only its clothing of trees, ferns, and mosses, but also a 'moraine profonde' of rock-stones and stems of dead trees, great and small, whereby the hills are being denuded, and the valleys, lakes, and channels gradually filled up."[1]

The soil is a thick, mossy, peaty, and spongy mass, and under the influence of gravitation, aided by alternate expansion and contraction, this slides down and drags with it the stones and boulders in the subsoil, till it reaches the border of a stream or the sea-shore, when its finer portions are carried away and the larger contents are left to accumulate.

In the Falkland Islands are some curious phenomena known as "*stone-rivers*"; these are deep accumulations of large blocks of stone which occupy the bottoms of the valleys, and though the gradients are slight, they move slowly and gradually down the valleys till they terminate in the sea after the manner of a glacier. The blocks are derived from certain bands of a hard rock, called *quartzite*, which are exposed along the sides of the hills and ridges; every little glen contributes its stream of angular fragments to swell the volume of that in the main valley. The movement appears to be due chiefly to the motion of the spongy soil-cap on which they rest, aided by the action of the trickling rain-water, which flows among and below the stream of blocks, and by the effects of alternate expansion and contraction of the blocks themselves.

Mountain Screes and Breccias.—In hilly and rocky districts, the materials accumulated by the action of rain and frost are much coarser than ordinary soils, and form deposits of angular gravel, which, in limestone regions, are sometimes cemented by the infiltration of carbonate of lime, and converted into what is called *breccia*.

In mountain districts every steep slope or cliff has its talus of fallen fragments produced by the agencies mentioned in Chap. VI. They are frequently of great length and breadth, and good examples may be seen in the hill districts of England and Scotland, where they are called *screes*.

[1] "Cruise of the Alert," p. 77, and "Quart. Journ. Geol. Soc.," vol. xxxvii. p. 348.

The enormous accumulations of débris among the Rocky Mountains, forming talus slopes 4,000 feet long, and 1,000 feet thick, have already been mentioned (p. 104).

The materials of a talus or débris slope are always travelling downward, being moved not only by gravitation, rain and snow, but by the mere alternations of temperature which on an exposed hill-side are often very great. When a stone resting on a slope is heated by the sun, its greatest expansion is in the direction of least resistance, that is along the downward side or edge; again, when cooled at night, its own weight prevents it from contracting so much upwards from the bottom as downwards from the top; both forces, therefore, tends to cause a slight downward movement of the stone.

In North Carolina, U.S.A., there are extensive spreads of angular débris, which have been described by Mr. W. C. Kerr. Some of the rock-fragments of which they are composed have travelled a distance of 6 miles from their parent sites, and now occur at the bases, or on the lower slopes of the mountains whence they have been derived. "They have crept down the declivities of the hills, exactly as a glacier descends an Alpine valley, by successive freezing and thawing of the whole water-saturated mass, both the expansion of freezing and gravitation contributing to the downward movement."[1] Snow also falling on such talus-slopes, and melting in the summer, would assist in giving motion to the mass.

Sir A. Ramsay acounts for the formation of the limestone breccias of Gibraltar in the same way.[2] These consist of "an accumulation of angular blocks of limestone embedded in a matrix of calcareous grit and earth, the whole forming a rock-mass as solid as the Gibraltar limestone itself. It varies in thickness from a few feet up to 30 or 40 yards. This is an old deposit, but he also describes a more recent one which has a similar composition, and occupies the position shown in fig. 51.

In this and other cases, where a coast-line has been elevated the angular fragments and débris of all sizes

[1] "Report of the Geol. Survey of North Carolina," vol. i. p. 156.
[2] "Quart. Journ. Geol. Soc.," vol. xxxiv. 1878, p. 505.

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limestones, which are wasted chiefly by chemical action, the insoluble residue remains on the surface of the parent rock, wherever the slopes are not steep, and forms the superficial soil. Thus, some chalk districts in the South of England are covered with a peculiar soil, called the clay with flints, the formation of which is explained as follows:—White chalk is nearly pure carbonate of lime, the percentage being from 96 to 98, with only 1 or 2 of insoluble matter; but it contains nodules of flint, which are likewise insoluble. The carbonate of lime is slowly, but continually, removed in solution by rain-water, and the insoluble residue gradually accumulates, forming a reddish loamy or clayey soil, full of flints. It is difficult however to separate the soil formed in this way from that derived from the reddish loams and clays which once overlay the English Chalk. This difficulty has led some geologists to deny the truth of the view that any clay with flints has been formed from the chalk, but the undoubted fact that similar red soils occur on limestone plateaux all over the world is a proof that they are so formed.

Such red earths are found in the hollows and channels of the Karren-felder mentioned on p. 88, and over the limestone districts of Istria and Dalmatia, where it is known as *terra rossa.* The same material forms the soil of the limestone plateaux of the Morea, and deep accumulations of it occur in places where it has been washed into hollows and depressions; in the rainy season all the streams are heavily charged with the red earth which has been washed into them, and this is carried down into the *katavothra,* described on p. 118. The limestone districts of the Southern States of America are everywhere covered by similar red residual clays.

Jamaica also affords a good illustration of the way in which red soils result from the subaerial detrition and solution of large tracts of limestone. Thick white limestones occupy more than half the surface area of this island, and form plateaux which are from 2,000 to 3,000 feet above the sea, and on which all the phenomena which such districts usually exhibit are developed on a conspicuous scale;—deep red soils, calcareous breccias, deeply eroded rocks, swallow-holes and subterranean caverns. The higher

raised coral-reefs of Barbados are also covered with a deep soil of red loamy clay.

The Bermuda Islands in the Atlantic afford another instructive instance. Except where covered by blown sand the surface rock of these islands is recent coral limestone, and it is everywhere covered by a red residual clay formed from the solution of the limestone. Sir Wyville Thomson has given analyses of this clay and of the coral rock from which it has been derived, and these show how relatively small are the quantities of the clay-forming materials in the original rock.[1]

Constituents.	Red Soil.	Coral Rock.
Combined water and moisture	18·265	0·328
Silica (as sand and clay)	45·156	0·052
Alumina	15·473	0·540
Peroxide of iron	13·898	
Lime	3·948	54·496
Carbonic acid	2·553	44·521
Sulphuric acid	Trace	0·214
Magnesia	0·539	1·751
Potash and soda	0·140	0·318
Phosphoric acid	0·704	0·080
	100·656	102·300

I Mr. ~~J~~. C. Russell has collected and discussed the analyses of some of the American red soils, and thinks they may be regarded as impure ferruginous kaolins.[2] They differ from ordinary clays which have been formed by mechanical disintegration and transport in the following particulars: they contain larger proportions of iron and combined water, they consist mainly of fine amorphous matter, comparatively free from the crystalline particles which are so numerous in ordinary clays and brick earths.

[1] "Voyage of the Challenger," vol. i. p. 325. But I have quoted the recalculated analyses given by Mr. ~~J~~. C. Russell in "Bull. U.S. Geol. Survey," No. 52.

[2] "Bull. U.S. Geol. Survey," No. 52, p. 40.

Laterite.—This material may be considered here, though its mode of formation, being rather uncertain, it might be given under a different heading. Laterite is a highly ferruginous clay, generally of a brick-red colour. The peroxide of iron is sometimes present in such quantity that it forms concretionary nodules of pisolitic iron ore containing 30 to 40 per cent. of metallic iron. When freshly dug it is soft, and may be cut into blocks which harden on exposure to the air and form a durable building stone.

Laterite is largely developed in India, especially on the Deccan plateau, where it is sometimes 150 or 200 feet thick. Several explanations of its formation have been suggested. Sir Charles Lyell thought it resulted from the decomposition of a deposit of volcanic dust. Others regard it as a product of the decomposition of highly ferruginous igneous rocks, such as basalt; and this probably has often been its origin, for lateritic soils are especially thick where basalt forms the underlying rock, and they are confined to tropical and subtropical countries where there is a luxuriant vegetation.

Organic acids formed from decomposing vegetable matter and carried down in rain-water are doubtless active agents in its production; and their action is increased by the climatic influences of such regions, and especially by the alternating periods of heavy rain and excessive heat, which are so highly calculated to induce a rapid disintegration of any rock exposed to them. For not only is there an ample supply of percolating water at one time of the year, but the heat of the dry season draws some of the underground water up again, and by its gradual evaporation in the surface soil causes it to deposit the iron it has leached out of the rock below in the form of the peroxide.

Still, this will not account for all laterites, some of which are considered by Mr. Blanford to be true detrital deposits of various ages.[1] He points out that they often rest on gneiss and other rocks, and that their seeming passage down into these rocks may be due to infiltration of iron from the laterite.

[1] See "Manual of the Geology of India," by Meddlicot and Blanford.

Cave Earth, &c.—When brooks and torrents are engulphed in open fissures and swallow-holes, the earthy materials which they carry along in mechanical suspension are deposited underground in the hollows of their subterranean channels. Thus the torrents of the Morea are usually charged with reddish mud, sand, and pebbles, when they enter the *katavothra*, but are pure and limpid when they flow out again. Inside the caverns are found deposits of red mud, containing pebbles and bones of various animals which had been washed in during the floods. Similar beds have been found in the caves of Malta and Gibraltar.

In most caverns, pieces of rock are from time to time detached from the roof, and the fragments are then embedded in the deposit forming below, which is frequently hardened by calcareous infiltrations, and converted into *breccia*. Such breccias are generally formed on the rocky floor of caverns, and are often overlaid by deposits of fine earth and loam, washed in through the cracks and passages communicating with the surface of the ground. These *cave-earths* are often many feet in thickness, and contain the bones of creatures which have inhabited the cave, or have been dragged in by beasts of prey.

Kaolin.—The formation of kaolin clay from granite is an excellent instance of the disintegration of a rock and the reconstruction of its materials. The mode in which the felspar of the granite is decomposed, has already been described (p. 91). The silicate of potash is removed in solution by rain-water, and the silicate of alumina is carried away in suspension. The latter, when re-deposited in hollows and valleys, forms the valuable beds of kaolin or china-clay, a hydrated silicate of alumina. Such deposits contain grains of quartz, scales of mica, and other impurities, which are separated by washing before the clay is exported to the potteries. Large deposits of kaolin occur in Cornwall and other granitic districts.

Loëss.—In many countries the wind plays an important part as a distributer of material, and in the formation of certain terrestrial deposits. Dust-storms on a small scale often occur in the English fenland during dry springs and summers, and occasionally a field has been

entirely stripped of its surface soil and of the seed sown in it. Sand storms occur in West Norfolk, and on the western side of the Wolds in North Lincolnshire.

Where the soil is dried and desiccated by the sun during the whole or greater part of the year, dust-storms are of frequent occurrence, and lead to the formation of enormous accumulations of dust. The *loëss* of central Europe and of China, the *black earth* of the Russian steppes, and the deep soils of Manitoba and Nebraska in North America, are all believed to be *æolian* or wind-made formations.

The European loëss is a homogeneous yellowish or light brown calcareous loam, breaking vertically, without any tendency to split into horizontal layers, containing only bones and shells of terrestrial creatures, and penetrated by thin tubules of carbonate of lime, which look as if they had originally coated the roots of plants. This deposit extends up to great elevations, to 4,000, and in the Carpathians even to 5,000 feet, while on lowlands, as in the valley of the Rhine, it is sometimes more than 200 feet thick. The *black earth* of Russia has similar characters, but the surface portion is mixed with vegetable matter, which gives it a black colour. Underneath it is of the same brownish hue.

In North China loëss deposits occur on an enormous scale, being in some places from 1,000 to 1,500 feet thick, and forming extensive plateaux at levels of 7,000 or 8,000 feet above the sea. Just as in Europe, the deposit exhibits no stratification, but has a strong tendency to cleave along vertical planes, so that it readily yields to the erosion of running water. These plateaux are in consequence trenched by a system of gulches and valleys, which present special and peculiar outlines, and form a curious type of scenery. The material falls in vertical slices which are easily broken up and removed by the streams, so that the walls of the valleys are perfectly vertical, and there is often a considerable space of level ground between, with here and there an isolated mass or pillar which has escaped destruction. Richthofen describes some of these walls as 500 feet high, and as affording habitation to the people of the country, who excavate chambers in the soft and yet firm material.

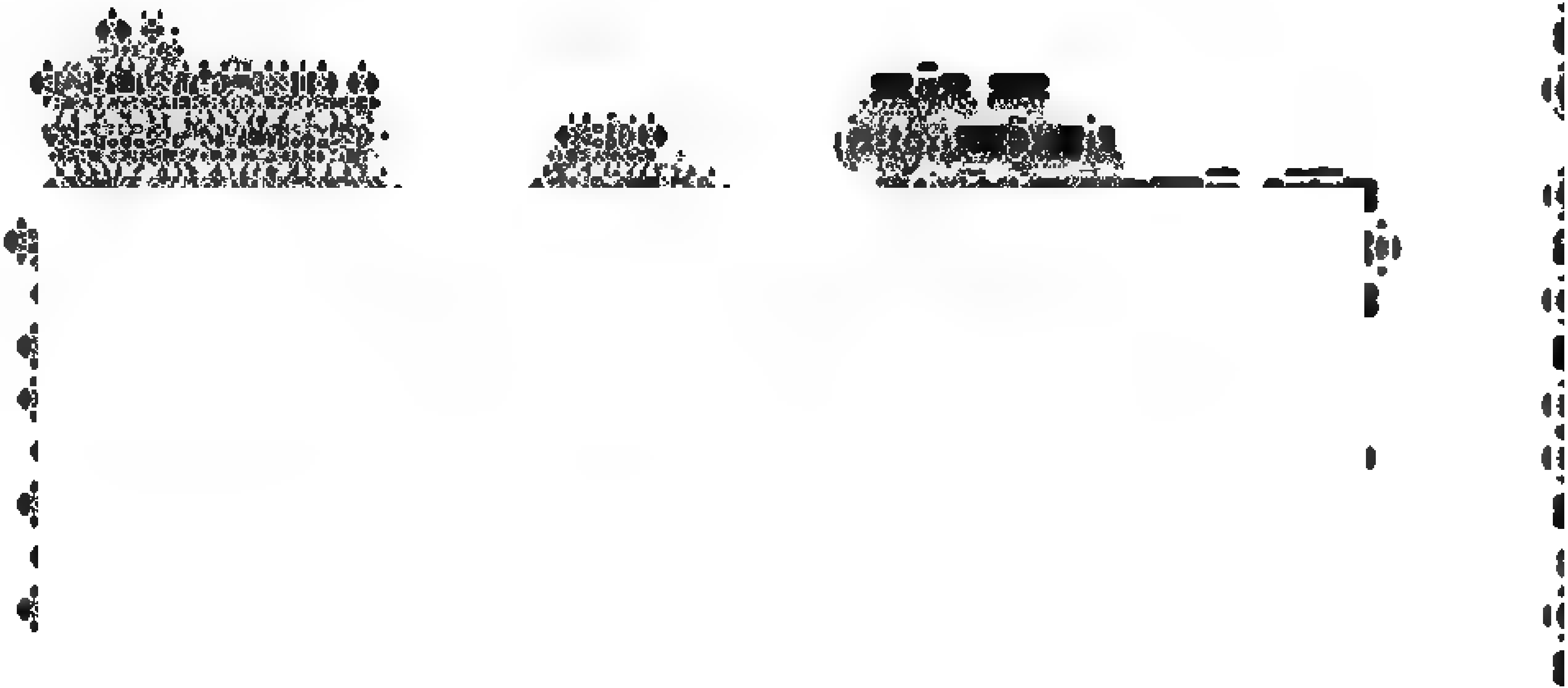

Fig. 52. A Valley in the Loëss country of North China (after Richthofen).

The ground above recedes in a series of steps with vertical faces, and tributary gullies enter the main valley and exhibit similar features for some distance as they ramify through the country (see fig. 52).

The manner in which these deposits have originated has been much discussed, but the only satisfactory explanation is that of Richthofen, who regards them as the result of dust-storms. Perhaps, however, he has laid too much stress on the necessity of arid conditions, and too little on that of damp surfaces; the material must have come from dry surfaces and have settled on damp surfaces, where a certain amount of vegetation existed, and small land shells were able to live. The conditions which led to the accumulation of such huge deposits in China and in Europe have passed away; but are still prevalent in some parts of central Asia. Thus in Khotan the sun is often obscured by clouds of fine dust, and where this falls a coat of yellow sediment is spread over the ground. The inhabitants say that it not only deepens the soil, but renders it more fertile, and they regard it as a manure of the greatest value.[1]

Blown Sand.—The sands blown off the shore by the wind drift into ridges and undulating tracts, called *dunes*, which often spread over considerable areas. On many shores these drifts continually advance inland and cover up fertile districts with barren sand; in other places the dunes form a bar across the mouth of some estuary, and cause the accumulation of silt inside which may eventually become habitable land.

As an instance of the former effect, the sand-drifts of the north coast of Cornwall may be cited; these have invaded a considerable area of cultivated land, and now form hills several hundred feet above the sea-level. This sand is largely composed of comminuted shells, and some parts of it are being converted into stone by the infiltration of carbonate of lime and oxide of iron.

Of the latter effect there are many instances on our eastern coast. Thus in Norfolk, between Eccles and Winterton, hills of blown sand have barred up and ex-

[1] The student will find the origin of the loëss discussed in detail by Baron Richthofen and Mr. Howorth, "Geol. Mag.," Dec. 2, vol. ix.

cluded the tide from many small estuaries. At Winterton there is an inland cliff about a mile long and some distance from the sea. Again, from Happisburgh, southwards, hills of blown sand extend as far as Yarmouth, where they spread out into extensive dunes.

In France, along the shores of the Bay of Biscay, the sands used to advance inland at the rate of 60 or 70 feet per annum, overwhelming houses and farms in their progress, but this has been arrested by the planting of pine forests.

Accumulations of blown sand are frequent on the coasts of Australia. Mr. Jukes[1] describes an instance on the eastern coast near Port Bowen, where large sandbanks are exposed at low water. "These dry rapidly under the hot sun and the trade-wind, which blows home upon the shore, then drifts the sand up upon the beach, and piles it into hills 50 or 60 feet high. Behind these hills is a large mangrove swamp, which is being gradually buried under the advancing sand. . . . Large districts, with hills of 200 or 300 feet in height, are found also on the coasts of Western Australia, stretching sometimes ten miles inland, formed of loose incoherent sand, once apparently drifted by the wind, though now brought to rest by the growth of a wide-spread forest of gum-trees. Parts of these sands, which consist greatly of grains of shells and corals, are compacted together into a stone, hard enough to be used for building, by the action of the rain-water dissolving some of the carbonate of lime, and re-depositing it on evaporation."[2]

Tracts of blown sand, however, are not confined to the vicinity of sea-shores; they are frequent in the deserts of Africa and Arabia, where they are formed from the disintegration of sandstones and arenaceous limestones. Many of the ancient temples of Egypt have been buried under drifts of sand, and the whole Egyptian valley would, doubtless, have been overwhelmed by the desert-sands if it had not been for the annual flooding of the country by the Nile. In Southern India, in the district of Tinnevelly,

[1] Jukes' "Manual of Geology," second edition, pp. 154, 155.

[2] For an interesting instance of travelling sands read Sir Wyville Thomson's account of those in Bermuda, in his "Atlantic," vol. i.

a sand-drift is described as advancing in a progressive wave and overwhelming fields and villages in its course. These sand-hills are being gradually driven from W.N.W. to E.S.E., that being the direction of the prevailing winds in the regions where they are situated. A comparison between surveyor's marks, fixed at various times since the year 1808, shows that the whole mass of hills is moving E.S.E. at the rate of about 51 feet a year. Efforts to arrest the drift, by planting trees, grass, and creepers, have as yet proved unavailing.

§ 2. *Chemically-formed Deposits.*

We have seen that all percolating water is able to dissolve certain portions of the rocks through which it makes its way, and to hold these substances in solution until it is evaporated.

When water containing carbonate of lime or other salts in solution is exposed to evaporation, each drop loses both water and carbonic acid, and becomes gradually saturated with the mineral matter, till it can no longer hold it in solution. Consequently, if the evaporation is continued beyond this saturation point, some of the dissolved carbonate must be deposited in a solid form on the surface, from which evaporation takes place. Deposits formed in this manner may be considered under three heads: (1) Surface incrustations; (2) Cavern deposits; (3) Deposits from springs.

1. **Surface Incrustations.**—The action of capillarity in soils and rocks has hardly yet been sufficiently considered by geologists. Water falling on dry ground is conducted downward by capillary action until it reaches that portion of the rock which is saturated with water, that is, the surface of the subterranean water-level. When rain is not falling, and the soil is being dried by evaporation from the surface, a reverse movement is set up, and water is drawn upward from the reservoir below, ascending by capillary action and passing into vapour at the surface. The vaporization of moisture from the surface of the ground is always visible on a hot summer's day, and it is the ascent of water from below that keeps the soil

moist in dry weather below the few inches of earth which are baked dry and hard. The capillary power of soils and rocks is greater in proportion to their fineness of grain, and the consequent minuteness of the pores or spaces between the component particles. Thus dry clay or chalk will take up water more rapidly than dry sandstone, and will part with it by evaporation more slowly.

It is obvious that as the ascending water is evaporated, the salts which it holds in solution will be deposited in the soil or on the ground. Thus it is said that in some parts of Greece, after the rainy season has ended and rapid evaporation has set in, saline matters rise to the surface in such quantity that the herbage is gradually killed by them, and only the very robust plants continue to grow.

Darwin has explained the incrustations of salt which occur on some of the mud-plains and pampas of La Plata by this action. After rain the salts disappear, and all the water-puddles are saline, but in dry weather the plain is covered with a crust, which is found to consist partly of sulphate and partly of chloride of soda.[1]

Mr. Maw has described a curious calcareous deposit in Marocco, a hard tufaceous crust, which forms a sheet-like covering over a large area of country. It varies in thickness from a few inches to two or three feet, and when broken often exhibits a banded agatescent structure. The underlying strata are soft limestones. Mr. Maw refers its formation "to the intense heat of the sun drawing up water charged with soluble carbonate of lime, and drying it layer by layer on the surface. The rapid alternations of heavy rains and scorching heat which take place on the Marocco plain, are conditions favourable to this phenomenon."[2]

2. **Cavern Deposits.**—*Stalactite and Stalagmite.*—Drops of water hanging from the roof of a limestone cavern are often coated over with a delicate film of carbonate of lime, like the finest tissue-paper. This gradually forms a little tube, which may be seen sometimes to acquire a length of some inches, still retaining all its fragility, until water trickling down the outside of it,

[1] "Geological Observations on South America," chap. iii.

[2] "Quart. Journ. Geol. Soc.," vol. xxviii. p. 89.

strengthens it by the addition of successive external coats. Ultimately such tubes will form long icicle-like pendants, which are called Stalactites and grow downward, while the drops which fall upon the floor result in an upward growth, called Stalagmite; and if the two ultimately unite a solid column of crystalline rock is produced. The name stalagmite is also applied to the sheets of the same material which are formed upon the sides and floor of the cavern (see fig. 32, p. 119); these often alternate with layers of earth and sand brought down by underground waters, so that the cavern is half-filled with deposits of various kinds. The following beds, numbered from below upwards, were found to exist in Kent's Hole near Torquay:—

5. Black Mould at surface.
4. Granular Stalagmite.
3. Cave earth.
2. Crystalline Stalagmite.
1. Breccia of rock fragments.

Sometimes in small caves the upper layers of stalagmite are so thick as nearly to reach the roof, and small holes and fissures are often completely filled with crystalline carbonate of lime.

3. **Deposits from Spring-Waters.**—Some springs are so saturated with carbonate of lime that as soon as they issue into the air they deposit layers of limestone, which, and when soft and friable, is called *Tufa*, and when hard is called *Travertine* or *Tiburstone*. A notable instance of a tufa deposit has been described by Mr. Maw as occurring in a ravine cut through the limestone hills near Caerwys in Flintshire.[1] The tufa extends up the valley in terrace-like ranges for three-quarters of a mile, and is in places more than 20 feet deep. It is for the most part of a soft marly nature, enclosing harder masses, which appear to have accumulated round plant remains, and it contains land and freshwater shells in abundance. A cavern lined with stalagmite occurs just above one of the tufa beds and seems to have given issue to the water which deposited them, but none now runs through it; and a stream from a

[1] "Geol. Mag.," vol. iii. p. 254.

source higher up the valley has cut a channel from 15 to 20 feet deep through the tufa beds.

Striking examples of travertine deposits occur at the Baths of San Vignone and San Filippo in Tuscany.[1] At the former place a large mass of travertine descends the hill whence the spring issues, and extends for the distance of more than half a mile. One stratum of it is 15 feet thick, and is so compact that it serves as an excellent building stone. At San Filippo the water which supplies the baths falls into a pond where it has been known to deposit a solid mass 30 feet thick in about 20 years. The mass which descends the hill here is a mile and a quarter in length, a third of a mile in breadth, and in some places attains a thickness of 250 feet. This deposit is abruptly cut off by a small stream which carries much away in solution to be utilized or deposited elsewhere.

It has been ascertained, however, that travertine is not always due to mere evaporation of water, and that some deposits formed in the water of hot springs are mainly due to the growth of a jelly-like alga, which has the power of eliminating carbonate of lime from the water, probably by absorbing the carbonic acid which held it in solution. Dr. Ferd. Cohn in 1862[2] showed that this was the case with the Sprudelstein of Carlsbad (see p. 114); he found that a jelly-like alga spread over the channels in which the water flowed, and that when squeezed little hard grains could be felt in its substance. Microscopical examination showed these to be grains of carbonate of lime, which, originating as minute crystals, grew by accretion into grains and clusters, and eventually amalgamated to form solid layers.

This has recently been confirmed by Mr. W. H. Weed, of the United States Geol. Survey, who found a similar growth in the water of the Mammoth Hot Springs of the Yellowstone Park. He describes the alga as growing in layers, each containing little crystals and stellate accretions which grow into grains, as stated by Cohn ; the grains being plainly visible in freshly formed layers of tufa, but indistinguishable in the older layers, where the grains are

[1] Lyell's "Principles of Geology," tenth edition, vol. i. p. 400.
[2] "Abhand. Schles. Gesell. Naturwiss," part ii. p. 35.

cemented together, and the oolitic structure is lost. This cementation of the grains, and of the laminæ containing them forms a firm more or less compact mass of travertine.

Gypsum.—Sulphate of lime is also deposited from some thermal waters. Certain springs in Iceland contain numerous sulphates in solution which have all been obtained from the decomposition of the volcanic tuff in the neighbourhood by the acids dissolved in the water.

Professor Bunsen found that if this tuff was pulverized and digested for a time in hot carbonated water, nearly all the constituents were dissolved in the form of bi-carbonates, the solution containing silicic acid, and the carbonates of lime, magnesia, soda, and potash, while the insoluble residue consisted of alumina and oxide of iron. If, however, the water was saturated with sulphuretted hydrogen, sulphides were formed, all being dissolved except the sulphide of iron. In hydrochloric and sulphurous acids all the constituents were dissolved.

Hence we see that various salts may be formed in such thermal waters according to the proportion of different gases with which they are impregnated. The formation of sulphuric acid, by the oxidation of sulphurous acid in contact with oxide of iron, would convert the salts into sulphates, and this probably takes place in the Icelandic waters. The sulphates in solution are principally those of lime and magnesia, with smaller quantities of the sulphates of alumina, soda, potash, and ammonia. On evaporation the sulphate of lime is deposited and forms floor-like layers of fibrous, sparry material, like the beds of gypsum so often met with in England. Beds of clay, often variegated with different colours, are also formed from the decomposition of the tuff.

Siliceous Sinter.—Other therma springs contain a large quantity of silica in solution, which is deposited as the water cools and evaporates, forming layers and incrustations of hard siliceous stone called Sinter. Deposits of this kind occur near the Geysers in Iceland. Analyses of the water of the Great Geyser show that the amount of solid matter in solution is about 120 parts in 100,000 of water, or 84 grains per gallon, nearly half of this being

silica and the remainder consisting of salts of soda and potash.

Professor Bunsen remarks that the silica is dissolved out of the felspathic lavas below and is held in solution as a hydrate by the alkaline carbonates and sulphates. He observes that "no trace of silica is precipitated on the cooling of the water, and it is only after the evaporation of the water that silica is deposited as a thin film on the moistened sides of the vessel, where evaporation to dryness takes place, whilst the fluid itself is not rendered turbid by hydrated silica until the process of concentration is far advanced."[1] The result of this is that the incrustations increase in proportion as the surface of evaporation expands with the spread of the water. Extensive deposits of siliceous sinter, or *Geyserite*, as it is sometimes called, are thus formed, one such being reported as 16 miles long, 2 furlongs wide, and 100 feet thick.

An analysis by Damour showed that the sinter had the following composition:—

Silica	87·21
Alumina and iron peroxide . . .	1·25
Lime	1·71
Traces of soda and potash . . .	0·66
Water of hydration	8·90
	99·73

Geysers also occur in New Zealand, and one near the lake of Rotomahana, formed beautiful terraces of sinter, which have been described by the Rev. R. Abbaye,[2] but they were entirely destroyed by the great eruption of Tarawera in 1886. The Geyser from which the water issued was situated on the border of the lake, and a hundred feet above its level; on the intervening slope the descending waters deposited their silica and formed a series of terrace-basins. These basins were mostly semicircular in shape, but varied much in size, some being very small, others extending for a length of 20 or 30 yards. The sinter itself contained about 97 per cent. of hydrated silica.

[1] De la Beche's "Geological Observer," p. 374.
[2] "Quart. Journ. Geol. Soc.," vol. xxxiv. p. 170.

The most wonderful exhibition of the phenomena connected with Geysers is to be found in the Great Geyser basin of the Firehole River in the Yellowstone Park, United States; Dr. F. V. Hayden thus describes the scene:[1]—"Ascending the Firehole, we find the surface on both sides the river covered with a thick siliceous crust, and completely riddled with springs of every variety. Quiet springs, with basins varying from a few inches to a hundred feet in diameter, are distributed everywhere. Some high pyramidal cones, with steam issuing from the summits, indicate the last stages of what were once important Geysers." Professor Geikie, in writing of this region says: "A prodigious mass of sinter has been laid down, and the form of the ground has been thereby materially changed. We made some short excursions into the forest, and as far as we penetrated the same floor of sinter was everywhere traceable." Another interesting feature of the region is the quantity of incrusted and silicified wood found scattered about the springs.

Recent examination of the sinter which is being formed in the geyser basins by Mr. W. H. Weed has resulted in the discovery that this deposit (like the travertine) is often largely due to the growth of plants.[2] In the hotter water these growths are filamentous algæ which become coated with silica, but in the pools of cooler water they form leathery sheets of tough gelatinous material, green, yellow, brown, or red, with coralloid and vase-shaped masses rising to the surface, and often filling up a large part of the pool. The tops of these growths unite into a flat crust which roofs over the pool, and often forms the floor of a new basin. The masses themselves consist of gelatinous silica in which the fibrous growth of the alga can be detected, and when the plants die there is a loss of water and shrinkage, with a gradual change to a cheesy kind of substance which appears to be hardened by a further precipitation of silica, due probably to the action of the decaying organic matter. The sinter thus formed is opaque, white, and often chalk-like in appearance, while that formed by evaporation is translucent, hard, and heavy;

[1] "Amer. Journ. Science and Arts," 1872, p. 161.
[2] "Ninth Annual Report of U.S. Geol. Survey," p. 650.

both kinds occur in some of the Geyser waters, and analyses show that the sinter formed by algous growth contains less water and consequently a larger proportion of silica than the other.

In the Grand Cañon of the Yellowstone immense deposits of silica, coloured every shade of red, yellow, and white, are seen to rest upon the irregular surface of an old lava-stream. The remarkable beauty of this valley is largely due to the exquisite delicacy and variety of these colours.

§ 3. *Organically-formed Deposits.*

Soil or Mould.—The mode in which ordinary soil or mould is formed, has already been described; its dark colour is due to the presence of decayed vegetable matter, but the quantity of this in ordinary soil or field earth is very small. In what is sometimes called vegetable mould the amount is greater. In one sample of fertile mould the amount of organic matter was ascertained to be only 1·76 per cent., in some artificially prepared soil it was as much as 5·5 per cent., and in the famous black soil of Russia from 5 to even 12 per cent.[1]

Dr. Darwin has shown that earth worms are largely concerned in the preparation of ordinary mould. In making their burrows they swallow the earth and pass it through their bodies, and he observes that the particles of the softer rocks suffer some amount of mechanical trituration in their muscular gizzards, in which small stones serve as millstones. He gives several instances in which a layer of earth two-tenths of an inch in thickness per acre has been annually brought to the surface by worms; thus, on good argillaceous pasture-land over the Chalk at Down, the accumulation during twenty-nine years amounted to 6½ inches of mould between the turf and a layer of chalk known to have been spread over the field in 1842. This shows a production of mould at the rate of 2·2 inches in ten years. Anyone who walks over a grass-plot, and observes the number of worm-casts, each consisting of from a quarter to half an ounce of fine black earth, must

[1] Darwin's "Vegetable Mould and Earth Worms," p. 238.

perceive that a very considerable disturbance of the soil is going on. In other countries larger worms make larger castings.

"The finely levigated castings when brought to the surface in a moist condition, flow during rainy weather down any moderate slope, and the smaller particles are washed far down even a gently-inclined surface. Castings, when dry, often crumble into small pellets, and these are apt to roll down any sloping surface. . . . The removal of worm-castings by the above means leads to results which are far from insignificant."[1] (See p. 190.)

Recent observations in Yorubaland, West Africa, by Mr. A. Millson, show that the work performed by worms in that country is still more extensive and important. The soil of the country is very fertile, and Mr. Millson attributes this fertility entirely to the action of worms. He says: "The whole surface of the ground among the grass is seen to be covered by serried ranks of cylindrical worm-casts, varying from a quarter of an inch to three inches, and existing in astonishing numbers. For scores of miles they cover the land, closely packed upright, and burnt by the sun into rigid rolls of hardened clay, which stand until the rain breaks them down into a fine powder." On digging down the soil is found to be drilled in all directions by worm-holes, and in the moist subsoil between one and two feet down the worms themselves are found. By collecting the worm-casts from a measured space, and weighing them, Mr. Millson found them to average 5 lbs. per square foot, which gives a total of 62,233 tons of subsoil brought to the surface over every square mile every year.

In other parts of Africa, as pointed out by Professor Drummond, the white ants perform a similar service. The large hillocks, five or six feet high, raised by these little creatures are well known; and Professor Drummond observed that the old hillocks, under the influence of tropical rains, gradually moulder down, the material being distributed over the neighbouring ground.

Even in temperate climes the work done by ants is probably considerable, for ants and earthworms rarely frequent

[1] *Op. cit.*, p. 306.

the same ground, and the renewal of soil on chalk downs, high sandy commons, and heath lands is largely due to ants. Old pastures may often be seen in England where ant-hills are so numerous as to be almost confluent with one another.

Formation of Peat.—In cold and temperate climates, various kinds of plants, which flourish in moist situations, increase and accumulate to such an extent that their decaying remains form large peat bogs or mosses. In England and Europe generally, some species of moss constitute the greater part of the mass, but elsewhere other plants contribute largely to the growth of peat. Darwin observed that in Tierra del Fuego almost all the plants contribute to its production, but especially a plant called *Astelia pumila* (Brown), and it is a singular fact that no mosses enter into the composition of the South American peat. In the English Fen-country the peat is chiefly formed of a moss called *Hypnum fluitans*, but in the mountain bogs of Ireland and Scotland the moss is a species of *Sphagnum*. Excavations in a peat bog show that on the surface grows the green living moss with many other plants. Two or three inches below that is a brown spongy mass, consisting of the fibres of dead plants; this passes gradually down into a compacted brown mass in which the vegetable tissue begins to disappear. Lower down it is still denser and darker, and all obvious traces of fibre and tissue perhaps are lost; until, at a depth of sometimes 30 feet, a compact black substance is found which cuts like cheese, but, except from it dampness, might be called soft coal.

The trunks and branches of trees are frequently found embedded in peat-mosses, especially near the bottom, where the wood is generally converted into a dark brown or black cheesy substance, soft when first uncovered, but hardening on exposure to the air. Such is the nature of the material known as Irish bog-oak. According to Sir J. Rennie, many of the peat-mosses in Europe occupy the site of great forests, some of which have been destroyed within historical times. The fallen timber, by obstructing the natural drainage and causing the ground to become wet and marshy, has conduced to the growth of the mosses

which produce peat. Thus, we are told, that the overthrow of a forest by storm, about the middle of the seventeenth century, gave rise to a peat-moss near Lochbroom, in Ross-shire, and that in less than half a century after the fall of the trees, the inhabitants dug peat there.[1]

Other peat-mosses occupy the sites of silted-up lakes and pools, which have been gradually converted into swamps. Many such swamps owe their origin to the damming up of streams by beavers, so that these industrious animals may really be ranked among geological agents. The authors of the "North-West Passage by Land,"[2] observe that the former operations of beavers in Canada must have been upon a very large scale, for "nearly every stream between the Pembina and the Athabasca, except the large river Macleod, appears to have been destroyed by the agency of these animals. The whole of this region is little else than a succession of pine-swamps separated by narrow ridges of higher ground, and it is a curious question whether that enormous tract of country marked *swampy* on the maps has not been brought to this condition by the work of the beavers, who have thus destroyed by their own labour the streams necessary to their existence." At one place they found a long chain of marshes formed by the damming up of a stream which had ceased to exist, the beaver huts had become grassy mounds on the dry land, and the dam in front was a green and solid bank.

Many peat-mosses extend over large tracts of land; one of the mosses near the river Shannon in Ireland is said to be 50 miles long with a breadth of 2 or 3 miles. The Great Dismal Swamp of North America is described by Lyell as an extensive morass 40 miles long from north to south, and 25 miles wide, between the towns of Norfolk, in Virginia, and Weldon, in North Carolina. "The surface of the bog is carpeted with mosses and densely covered with ferns and reeds, above which many evergreen shrubs and trees flourish, especially the White Cedar and the deciduous Cypress. . . . On the surface lie innumerable trunks of large and tall trees blown down by the winds, while thousands of others are buried at various depths in

[1] Rennie's "Essays on Peat," p. 65.
[2] Lord Milton and Dr. Cheadle, *op. cit.*, pp. 178, 211.

the mire below. The soil to the depth of 15 feet is formed of organic matter, without any admixture of earth."[1]

Near river mouths large tracts of land sometimes pass into the condition of fens or marshes, parts of which support a growth of peat-moss. The Fens of Norfolk and Cambridgeshire, the Lewes Levels, Pevensey Marshes, and parts of Denmark and Holland are examples. The surface peat of the Fen-land varies in thickness from 1 to 18 feet; when it is thick enough to be dug for fuel, the uppermost 10 or 12 inches are seen to be dark brown in colour and consist of an amorphous mass of roots, rushes, and moss; the lower portions are quite black, and are bedded in regular layers, the vegetable structure is more obscure, but the mass seems to consist almost exclusively of moss.[2] In Norfolk and Cambridgeshire alone, an area of more than 500 miles is occupied by peat. Excavations in this Fenland show, moreover, that there have been many periods during which the peat-moss grew and flourished, for subterranean beds of peat occur at various depths, as many as five having been found one below the other, separated by deposits of clay or silt; just as coal-seams are separated by beds of clay or sandstone.

Remains of forest trees are abundant both in the surface peat as well as in the subterranean deposits; indeed these relics are so abundant in many places, that it is evident that extensive forests have existed from time to time, and in these localities it may have been the destruction of the forests that gave rise to the formation of peat. The trees which grew in these forests were chiefly oak, elm, birch, yew, willow, and sallow; their roots and stumps are frequently found still in the position of growth, and the fallen trunks are often from 40 to 60 feet long. It is remarkable that these trunks almost always lie in one direction, viz., with their tops towards the N.E., as if they had been blown down by winds from the S.W.

We can well imagine that when conditions ceased to be favourable to forest-growth, and the ground became marshy

[1] "Principles of Geology," vol. ii. p. 506, and "Travels in N. America," vol. i. p. 143.

[2] Skertchly, "Geology of the Fenland," Mem. Geol. Survey, p. 134.

and boggy, the stagnant water and the growth of peat would cause the decay of the trees. Thus enfeebled, they would ultimately yield to the force of storms from the S.W., and falling, "be entombed in the material which, their destroyer in life, became their preserver in death."[1]

Mangrove Swamps.—In tropical countries similar accumulations of vegetable matter exist in the mangrove swamps which are formed along low-lying shores and near the mouths of rivers. The estuary of a tropical river is generally bordered by mangrove swamps, and the trees seem to flourish best where they are within the influence of the tide. At low water the stems are seen to be supported by a tangled mass of branch-like roots, which rise out of a bed of thick, black, unctuous mud. Small crabs and other marine creatures crawl over the mud; oysters fasten themselves to the mangrove roots, and often form huge clusters of many hundreds together; decomposing vegetation is everywhere, and the atmosphere of the swamp is close, damp, and malarious. But as the tide rises and spreads over the swamp the roots are concealed and the trees then appear to be growing in the water, presenting a much more picturesque appearance.

The following description of mangroves and their habits is quoted from Captain Nelson's memoir on the Bahamas:[2] "The Mangrove (Rhizophora) seldom grows more than 15 feet in height; the strength and durability of its timber are very great, and from its development of roots and its amphibious habit, it is an important agent in the conversion of swamps and littoral tracts into dry land. There are many species, but the most common in the Bahamas are the yellow and the white mangroves. The yellow mangrove sends out horizontal roots inland, and into the water it throws down numerous vertical radicles or branch-like roots (to which a variety of living things soon become fixed); it also throws off bud-plants, which dropping from the surface into the water, float until they attain a mud-bank or rock-head or other congenial point of fixture. The white mangrove throws down no pendants, but on every quarter it throws off roots which penetrate the mud hori-

[1] Skertchly, *op. cit.*, p. 164.
[2] "Quart. Journ. Geol. Soc.," vol. ix. p. 210.

zontally about six or eight inches under the surface, and send up suckers at every three or four inches of their course. Thus each species by the multiplication of roots and stems becomes an effective agent in the retention and increase of soil, and frequently both combine in their work of encroachment on the water and the formation of land; as is well seen along the north-east shore of Cunningham Lake. In the swampy clay and sand of the Florida coast, the mangroves form dense jungles from five to twenty miles broad, and running up the creeks and inlets."

Captain Nelson also observes that other and much smaller plants contribute largely to the formation of new land in the Bahamas. "The marshy lands that are gradually taking the place of the creeks and brackish lakes, abound with and may be said at some points to consist largely of a highly calciferous moss-like Conferva, which in concert with mangrove roots, grasses, and other plants consolidates and completes the chalky soil."

In Brazil also the mangrove is an efficient agent in aiding the silting up of the large lagoons which border the coast. When by deposition of sand the bottom is brought up to the level of low tide the seeds of the mangrove take root, and the shoal is soon covered with the trees. Among their roots fine silt is deposited, and the sandbank is overlaid with a layer of soft sand, which may increase in thickness till its surface is only covered at high water. Reeds, rushes, arums, and coarse grasses then assist in converting the swamp into land.[1]

[1] Hartt's "Geology of Brazil," p. 222.

CHAPTER XII.

FLUVIATILE DEPOSITS.

Deposits formed by Rivers and Glaciers.

Deposition of Detritus.—It must be borne in mind that the three processes, erosion, transportation, and deposition are closely connected; each may proceed in close neighbourhood to the other, and the hollow which has been formed by erosion one day, may be filled up with sediment on the next. It is seldom that the exact conditions of equilibrium exist, when the velocity of the stream is sufficient only for the transport of sediment without exercising

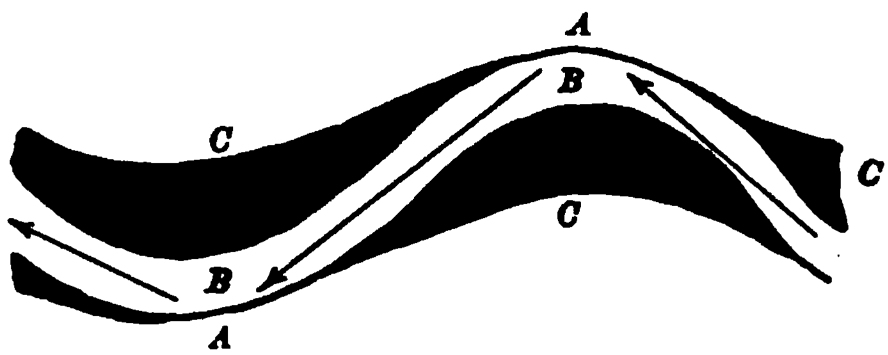

Fig. 53.

erosion or permitting deposition. For suppose that at a given time or place, the velocity is just enough to keep the load of detritus in suspension, it is clear that a slight rain-shower causing an increase in the volume of water, would at once convert the load into an agent of erosion, while conversely a decrease in the volume would allow some of the load to subside. Speaking generally, therefore, we may say that when the load is not employed in erosion, some of it is being deposited.

In the upper part of a river-course where the slopes are

steep, and the current swift, only the larger stones are allowed to rest; lower down the valley, where the stream loses some of its velocity, smaller stones and coarse sand are deposited, though much of the latter is still carried onward. Eventually this also subsides, and when a great river reaches the broad plains which are little above the level of the sea, it carries nothing but the finest silt and mud, part of which is deposited, and part is poured into the sea.

A winding river is constantly changing the position of its curves, for the stream is continually eating away the bank on one side of a curve and allowing deposition to take place on the opposite shore. The cause of this is found in the fact that the whole of the water in the stream does not move with the same velocity, and that the line of quickest motion does not keep exactly midway between the banks, but follows the course indicated in fig. 53, the arrows showing the impact of the current at the points A A. Since, therefore, the velocity of the stream is least off the points B B, and since decreased velocity means decreased power to transport detritus, it follows that deposition will take place opposite B B, and the angles will gradually be filled up with gravel, sand, or silt, as the case may be. This is shown by the black parts, C C, in fig. 53.

Gravel Beds and Alluvial Levels.—When a stream has reached a tract where the lessened slope allows gravel and sand to be deposited, small areas of these deposits are usually found to occur at intervals, first on one side of the river, and then on the other. They are slightly above the flood level of the stream, because, since they were formed, it has deepened its channel and consequently flows on a lower plane than it previously did.

Still lower down, the watercourse itself is generally bordered by strips of level ground, which form a narrow tract or plain, with the stream winding from side to side within it, and over which the waters spread in time of flood. The soil of this flood plain or alluvial level consists partly of earth conveyed by rain down the sides of the valley, and partly of the silt and mud deposited by the overflow of the stream; when the stream is in flood, and overflows this flat and shallow ground, the turbid current

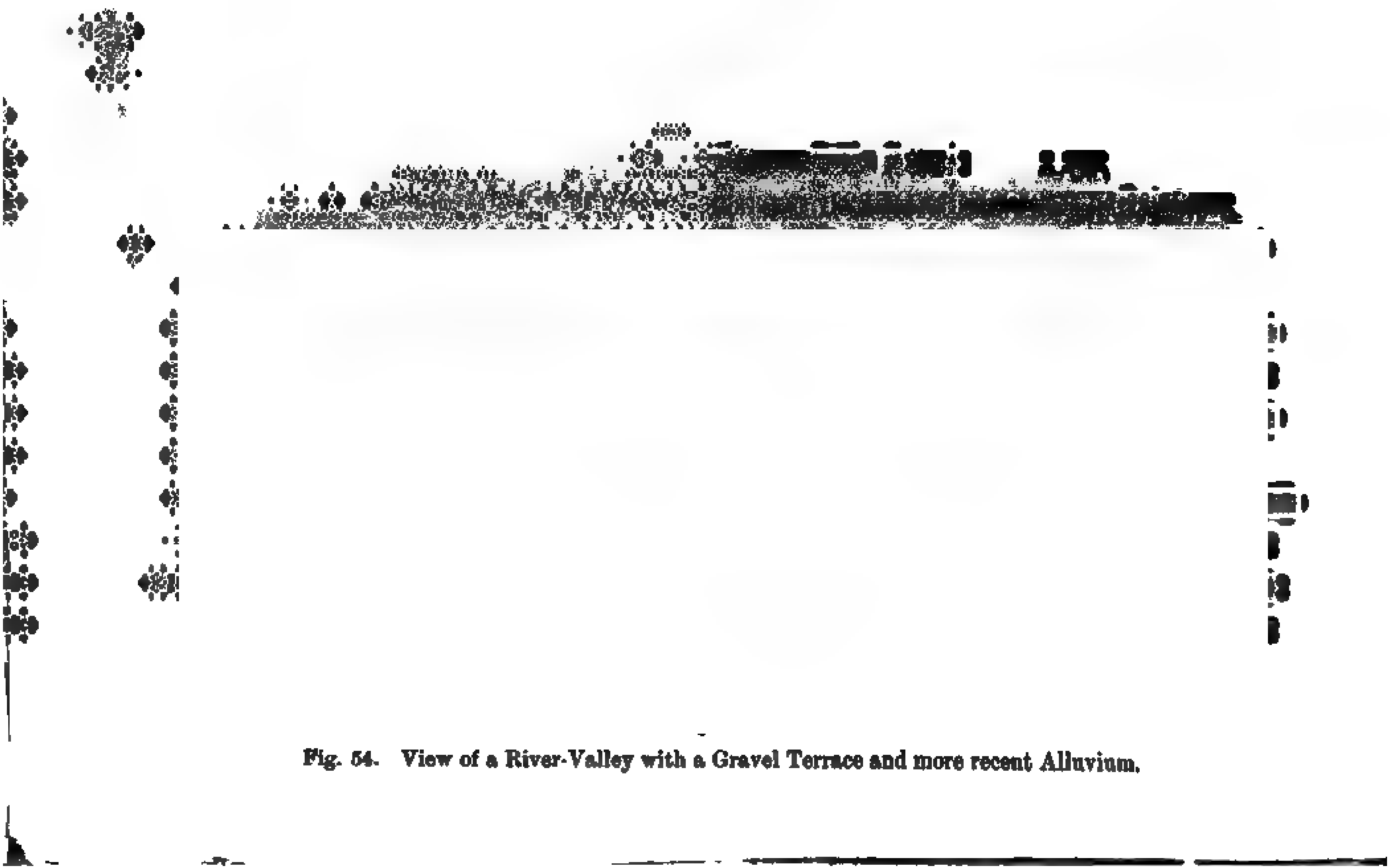

Fig. 54. View of a River-Valley with a Gravel Terrace and more recent Alluvium.

is checked, and being unable to carry all its load of sediment, some of it is precipitated to the bottom and remains there on the recession of the waters; this muddy soil is called *alluvium.*

In descending a valley it will always be found that the width of the alluvium increases in proportion as the volume of the stream increases, and within this constantly widening plain, the river pursues a tortuous and meandering course. At the same time the tracts of gravel increase in size and in height above the river-level, and often form extensive banks and terraces on either side of the alluvium.

Fig. 54 shows a river emerging from hilly ground and flowing towards the spectator: alluvial levels are seen on each side of the valley: on the right (at T) is a tributary stream winding through the deltoid flat it has helped to

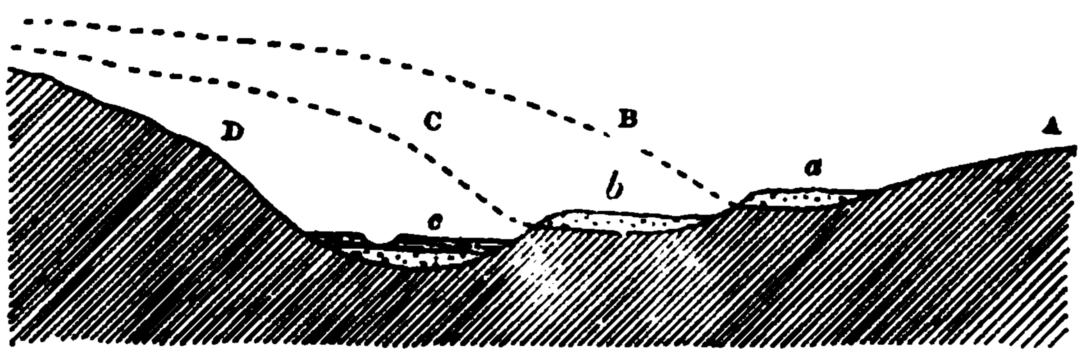

Fig. 55. Section through terraces of River Gravel.

form, and on the left (at G) is a bank consisting of gravel deposited by the river when it flowed at a higher level, and before it had cut out its present channel.

In many valleys patches of gravel may be found at various levels above the river, and sometimes at considerable distances from the present stream. These are portions of still older gravel beds deposited at a time when the river ran at that level, and before it had cut its channel down to its present depth. These higher banks of gravel have necessarily suffered much from erosion and detrition, and are generally reduced to the state of disconnected patches; but in some cases they are better preserved and remain as more or less continuous terraces, so that the valley side presents a succession of such gravel terraces, and a section across it has the appearance exhibited in fig. 55.

It must not be supposed from this diagram that the

terrace, *a*, originally extended all across the width of the present valley from A to D. At the time of its formation the valley was both narrower and shallower, its limits lying between A and B, and its western side being indicated by the broken line. As the stream, continually impinging on one bank, cut this side farther and farther back, the valley was both deepened and widened, and the terrace, *b*, remains to testify its extension from A to C. Each bank of gravel was, of course, deposited on the bottom of the valley for the time being, just as the latest gravel, *c*, occupies the bottom of the present valley, and has been deposited since the portion of ground between C and D has been cut away by the erosion of the stream.

Fig. 56 is a section through a real terrace of gravel at Barnwell, near Cambridge, and is drawn to a definite

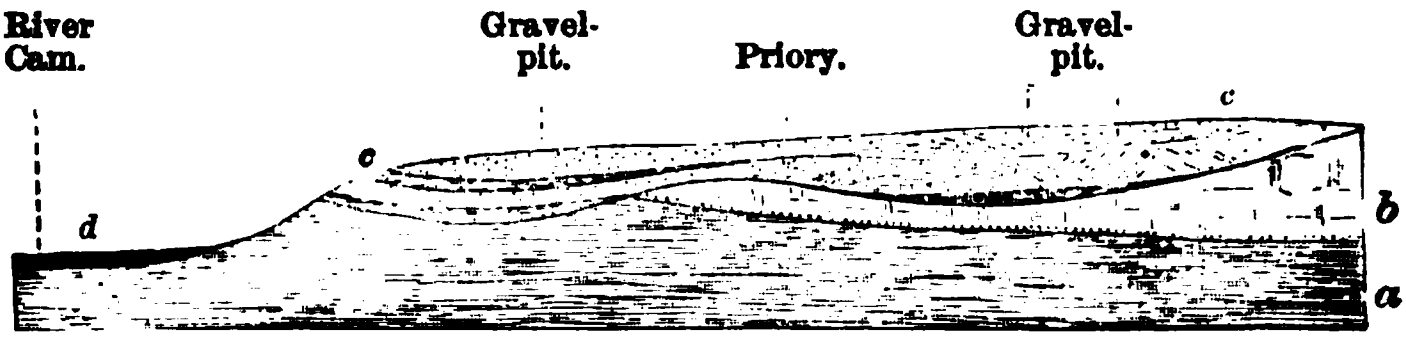

Fig. 56. Section through the Barnwell gravels, Cambridge. *a*, gault. *b*, chalk-marl. *c*, sand and gravel. *d*, alluvium.

scale. The extent to which the river Cam has lowered its bed since the formation of this old gravel flat is shown by the position of the modern alluvium. At the Priory pits the gravel is about 20 feet deep, and it contains beds of fine sand and loam, with many land and river-shells. On the opposite side of the river is another flat of sand and gravel at an intermediate level; the Barnwell terrace being about 25 feet, and the Chesterton terrace 15 feet above the river.

The diagram, fig. 55, represents the usual relation of the gravel terraces to the rocky slope below, each terrace being a separate deposit, and quite disconnected from that above or below. It frequently happens, indeed, that strips of the underlying rock are exposed along the slopes which intervene between the terraces. There are some cases,

however, where a section through the valley would present the appearance of fig. 57. Such cases are found where the whole country has been depressed since the formation of the great valleys, so that these have been filled up with deposits of sand and clay during the submergence. Subsequent elevation of the land has allowed the rivers to cut new channels through these deposits, and the velocity of the streams increasing *pari passu* with the amount of upheaval, their capacity of vertical erosion increased while that of lateral erosion diminished, so that the width of the flood-plain has gradually contracted, leaving a series of benches or terrace levels carved out of the mass of material accumulated in the valley.

Instances of such terraced valleys have been described in North America, and are so prevalent that the period of their formation is known as the *Terrace epoch*. They also

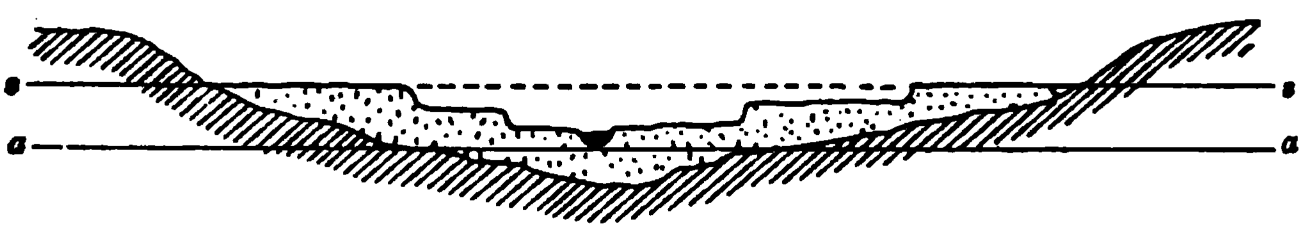

Fig. 57. Terraces cut out of a silted-up Valley.

occur in Patagonia under similar conditions, as described by Darwin.[1] In such cases the number and levels of the terraces correspond on each side the stream, but in England there are few instances of such valley-structure, and terraces seldom occur at exactly the same level on opposite sides of a valley, except where an alteration in the course of the stream has caused it to cut through an old terrace, and so to leave a portion on either side of the present channel. Where two opposite terraces appear to correspond, it will generally be found that the level of one is really lower than the level of the other, and that they have been formed at different epochs in the excavation of the valley.

In the north-west of England and in Scotland some valleys appear to exhibit a structure like fig. 57. The

[1] "Journal of Researches, Voyage of the 'Beagle,'" ch. ix. p. 128, Minerva Library edition.

valleys of the Mersey and Irwell in Lancashire are said to be instances of this, and Mr. De Rance has drawn a section showing the terraces on the western side of the Irwell, near Pendleton, which are apparently cut out of a continuous deposit of gravel. The surface of the river here is about 70 feet above the sea, and the highest terrace is 100 feet above the river ("Proc. Geol. Assoc.," vol. iv. p. 231). Here also there has been elevation since the filling up of the original valley.

Where two streams join, or a tributary enters a main valley, there is almost always a tract of gravelly deposit in the angle between the two channels. As the streams deepen their channels, the point of junction is shifted further and further down the main valley, and the triangular gravel-covered area is consequently elongated and increased. Often also it presents two or more terraces, and, as Mr. H. Miller has pointed out, these junction terraces are produced independently within the recess, and may not be on the same levels as the terraces in either of the valleys.[1]

That river-terraces are produced thus locally and independently is a proof that their formation is simply a result of the manner in which rivers erode and deepen their channels, and not on any variations in the volume of water. The process of river-terracing may sometimes be witnessed on a miniature scale where the water from a spring flows over a sand flat. Mr. Miller mentions such a case where spring water flowed over a smooth beach of fine sand bordering a river: "It had its curves, its deflection-banks, at the base of one of which it was still scooping with a force that drove away a brush of sand-grains as if they had vitality in them; and opposite these little cliffs it had its terraced slopes left to one side because the stream had pushed to the other, and marked by the finest possible engraving of terrace-lines, *not* at equal heights where they chanced to stand opposite." He convinced himself that all these effects had been produced by a steady volume of water, unaffected by floods or by falls in the level of the river below, "but simply by planation at different levels

[1] "On River-Terracing," Proc. Roy. Phys. Soc. Edin. 1883, p. 288.

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The head of the delta is the point where the river originally entered the lake or sea; properly speaking, indeed, the river ends here just as its valley ends, and its waters merely find their way as best they can through the muddy deposit with which it has choked its own mouth. This they do by means of several channels branching off from the main stream, each of which conveys a portion of muddy water to its own mouth, where the sediment is deposited, and the extent of the delta is thus continually increased.

The Rhine when it enters Holland is lost in a great deltoid flat among a number of bifurcating channels, in which its waters are mingled with those of the Meuse, Sambre, and other rivers; these have all contributed to form the low marshy ground of which the Netherlands consist.

The delta of the Rhone has many points of interest; the amount of sediment brought down by the river has been mentioned on p. 134; this is discharged into the Mediterranean, and has formed a delta which has a front of about 50 miles, and its head is 25 miles from its edge. Under the Roman dominion, 400 B.C., Arles was only 14 miles from the river mouth, now it is 30 miles, hence this delta has advanced 16 miles in 2,200 years. The depth of the deposit is also considerable, a well sunk at Aignes Mortes passed through 328 feet of marls and clays without reaching the base of the delta.[1]

The united deltas of the Po and Adige have a length of about 70 miles from Ostiglia to the mouth of the Po, and a seaward breadth of about 50 miles; but they are conterminous with the deltas of the Brenta, Piave, Tagliamento, and Izonzo, so that a continuous tract of marshy land extends for more than 100 miles from the Gulf of Trieste nearly as far as Ravenna. Adria, which was a seaport in the time of Augustus, and gave its name to the Adriatic Sea, is now 20 miles inland, and the whole coast-line above indicated has increased by a width of from 2 to 20 miles during the last 2,000 years. All this material has been brought down from the Alps by the tributaries of the above-mentioned streams.

Many deep wells have been sunk at Venice, and one of

[1] C. Martius, cited in Prestwich's "Geology," vol. i. p. 85.

them has been carried to 572 feet without reaching the bottom of the sands and clays of the delta. The deposits consist of yellow sands, brown and grey clays, with beds of lignite and dark carbonaceous sandy clay, sands prevailing in the lower part, clays and lignites in the upper. Most of the sands contain marine shells, but freshwater species occur in the lignites.

The delta of the Mississippi has an area of 12,300 square miles; it has completely filled up the inlet of the sea which once penetrated deeply into the North American coast, and has projected far into the Gulf of Mexico, carrying out the river by a natural canal 50 or 60 miles beyond the general edge of its delta. The head of this delta taken as the point where the river sends off its first bifurcation (called the Atchafalaya) is about 200 miles distant from the coast. A well has been sunk at New Orleans to a depth of 630 feet without reaching the bottom of the alluvial deposits. This boring passed through alternations of clays and sands, the latter predominating in the lower part of the series. There were eighteen distinct beds of clay, one being 63 feet thick, and their combined thickness being 266 feet; several of them are marly, and effervesce with acid. Four beds of lignite were found, the lowest occurring at 150 feet. Below a depth of 40 feet the fossils were all marine and of recent species, showing that the delta has simply displaced the waters of the Gulf of Mexico.

The conterminous delta of the Ganges and Brahmapootra is still larger, for it makes a coast-line of 260 miles in length, and a swampy flat which is 100 miles wide at a distance of 250 miles in the interior, its whole area being probably 50,000 or 60,000 square miles. An Artesian well was bored at Calcutta to a depth of 480 feet, the auger penetrating some old land surfaces at several depths, proving continued depression of the land (Lyell). This well is also remarkable for the fact that the lower 80 feet of the boring consisted of sand, shingle, and boulders, showing that the velocity of the stream and, therefore, the slope of its water-course, must have been very much greater at that time, and that subsequent depression of the land has lessened the velocity of the stream, and consequently the rate of

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of course, slowly silting-up, and will eventually be dry land.

We need hardly observe that river-valleys do not always terminate in deltas. There are many great rivers which do not block up their own mouths in this way, but pour all their detritus directly into the sea. In some cases the strength and velocity of their currents is sufficient to carry the greater part of the sediment out beyond their mouths; in other cases the estuary into which the river falls is kept open by the scour of the tides. The Amazons and La Plata are instances of rivers with strong and rapid currents which are felt at a distance of more than 100 miles from their mouths; the Thames, Severn, and other rivers of our own islands which empty themselves into estuaries, illustrate the latter case. Neither do the deltas of large rivers give us the full account of the erosion they have performed, for a large amount of sediment is still poured into the sea and distributed over its bed by the action of marine currents. A delta is, in fact, only a part of a bay or estuary which has been filled up with the sediment carried into it by a large river. As we have seen, the sediments enclose shells of marine species, and they might be described under the head of marine deposits, but it was more convenient to treat of them in connection with the rivers which supply the material.

§ 2. *Deposits formed by Glaciers.*

Moraines.—The moraines of a glacier have already been described (p. 154), and it was stated that on the retreat of a glacier its terminal moraine will remain and form a semicircular mound stretching across the valley.

Such a moraine consists of a confused mass of earth, stones, and boulders heaped together without any regard to size or weight; most of the materials have been shot over the end of the glacier, just as rubbish is thrown down to form a railway embankment. The greater number of the stones, therefore, having been carried on the upper surface of the glacier, will not bear any glacial markings or scratches; those, however, which were fixed in the under surface of the ice, and came in contact with the rocks form-

ing the sides and bottom of the valley, will be polished and scratched on one or more faces.

Old lateral moraines are also found where ancient glaciers have melted away, these moraines remaining as long hummocky ridges or banks along the sides of the valley, and consisting of similar materials to those which compose the terminal moraines.

Examples of such moraines are to be found in many parts of the British Islands, where glaciers formerly existed, viz., in North Wales, in the Lake district, in the highlands of Scotland, and among the hills of Ireland. An excellent example occurs near Killarney, at the northern entrance to the Gap of Dunloe, as described by Mr. Du Noyer.[1] Three lunette-shaped mounds of morainic material, sand, gravel and boulders, are arranged in a rude concentric form, one beyond the other across the mouth of the gap; the two outer mounds are incomplete, their western extremities having been destroyed, but the portions remaining on the east side of the stream measure fully one mile in length by about 100 yards in width, and their south-east ends rest on the flank of Purple mountain at an elevation of about 400 feet. The inner mound is much more perfect, and is cut through in its central part by the river Loe; on the east side of the river it measures 650 yards in length by 150 in width, and on the west side it curves round to the S.W. for a distance of 700 yards. At the north end of the Black Lake is still another deposit left by the retreating glacier, as the climate became warmer.

During the later stage of the Glacial period the higher parts of the Scottish Uplands nourished groups of glaciers which have left numerous well-marked moraines.[2]

A large series of them occur in the valley of the Dengh, a tributary of the Ken (Kirkcudbrightshire). "The mounds are arranged in concentric lines, sometimes conical in shape, but generally assuming the form of narrow ridges which often trend towards the centre of the valley. Road cuttings show that the moraine matter consists of a sandy clay with numerous subangular stones, which in many instances have irregular striations." These mounds are traceable down to

[1] Explanation of Sheet 173 of "Geol. Survey of Ireland," p. 23.
[2] "Mem. Geol. Surv. Scot.," Sh. 9, p. 41; Sh. 15, p. 40.

and across the valley of the Ken, where they rest upon a thick deposit of tough boulder clay.

In the valley of the Holm Burn, another tributary of the Ken, there is a similar series of moraine mounds, most of them forming long winding ridges with a marked bend towards the centre of the valley, and beautifully illustrating the common horse-shoe shape of moraines. They consist of loose gravelly and sandy earth with well-rounded stones, of which in one section one-fifth were found to be ice-scratched, but in other places the proportion is much less.

Till and Boulder Clay.—Ordinary valley-glaciers do not appear to leave any deposits behind them besides the moraines above described. The glaciers of Switzerland have sometimes retreated for considerable distances, leaving the ground they formerly covered exposed to view; consequently, if any deposits were formed underneath the ice, we should expect it to remain on this ground.

It does not appear, however, that such deposits ever occur. Professor Bonney,[1] who has specially examined retreating glaciers for this purpose, thus writes:—"In no case have I been able to find signs of any deposit resembling till or boulder clay; the detrital matter, which is scattered generally sparsely over the slope left bare by the retreating glacier, has fallen from its surface, like ordinary terminal moraine," neither could he find any such deposit under the ice of the glacier itself.

A similar absence of deposits has been remarked in Norway.[2] Professor Spencer noted several points of contact between glaciers and their rock-beds, but found nothing like boulder clay under the ice, though he observed a glacier advancing over an old terminal moraine which was partially levelled and probably compressed in the process.[3]

It is said, however, that these glaciers are too small to have the power of forming boulder clay, and that in the present climates of Norway and Switzerland the fine mud

[1] "Notes on Glaciers," "Geol. Mag.," Dec. 2, vol. iii. p. 197.
[2] See "Proc. Geol. Soc. Liverp.," 1872-73, and Spencer in Geol. Mag. Dec. 3, vol. iv., p. 168.
[3] See also Bonney, *op. cit.*, p. 198.

is all carried away by the sub-glacial streams instead of accumulating to form a pad of clay or *Ground-moraine,* as it would do if the climate were more severe. It has been supposed that the case is different in the Arctic and Antarctic regions, where the glaciers are not confined to the valleys, but form a confluent sheet of ice spreading over the whole country, and that under these conditions a mass of débris must accumulate underneath the ice, and may form a deposit of considerable thickness.

This accumulation must be partly frozen into the bottom of the ice, but it is supposed that some of it is pushed along by the moving ice-sheet, and that portions are detached and allowed to accumulate in hollows and valleys underneath the ice. Furthermore, it is assumed that the ice-sheet passes over such deposits, and allows them to remain undisturbed, notwithstanding the erosive powers usually attributed to moving ice. Finally, it is said that the great weight of the superincumbent ice will exercise an immense pressure upon the material below, and compact the mud and stones into a tough boulder clay.[1] This hypothesis was framed to account for the formation of the hard and tough kind of boulder clay known in Scotland by the name of Till, but Professor James Geikie has since applied it to explain the origin of all other boulder-clays.

It is not, however, a completely satisfactory explanation, while as a matter of fact no one has yet observed boulder-clay in the Arctic regions occupying such a position with reference to the inland ice as would suggest the inference that it has been formed by or beneath the ice. There is, indeed, a general absence of any kind of moraine deposit over those areas, which are free of ice; bare rock is almost everywhere exposed. Professor Nordenskiold, describing ground which had but lately been abandoned by the ice, says it exactly resembled the woodless gneiss districts of Sweden and Finland, the rounded hills of gneiss being covered with erratic blocks and divided by valleys with small lakes and scratched rock surfaces, "*on the other hand, no real moraines were discoverable.*"[2]

Again, Lieut. Lockwood describes the ice-cap of central

[1] See "Great Ice Age," by J. Geikie, second edition, ch. i.
[2] "Expedition to Greenland," "Geol. Mag.," vol. ix. p. 362.

Grinnell Land as free from rock débris except in a valley confined by high mountains. The ice-wall is from 120 to 200 feet high, and along its foot there were only here and there small ridges or banks of moraine deposit.[1] Nordenskiold observed similar small banks in Greenland.

The following are difficulties in the way of accepting Professor J. Geikie's theory.

1. No one has yet seen any traces of a ground-moraine under a retreating glacier or an ice-sheet.

2. Actual observation has only shown that where glaciers descend a slope they rest on bare rock and push all loose materials before them; where they reach more level ground they pass over any accumulation of débris without much disturbing it.

3. Boulder clay is not only found in valleys and plains, but has been spread over high ground and low ground alike in a thick and continuous sheet.

4. Boulder clay frequently contains fragments of rock, the parent sites of which are several hundred feet below their present resting-place. They must, therefore, have been carried up by the agent which formed the clay, but it has not been proved that an ice-sheet can move up a slope for any considerable distance.

5. There is inconsistency in assuming the existence of a great underlying sheet of ground-moraine, and at the same time crediting the ice with the power of excavating lake basins. Neither one nor the other theory has yet been proved.

It would appear, however, that land-ice can in some way give rise to the formation of a boulder-clay, that is, a stiff clay containing many stones. Such clays, mingled with loose gravelly deposits, are described by Sir Charles Lyell and others as occurring at several places on the great plain which lies between the Alps and the Jura. It was stated on p. 155 that there was a time when the Swiss glaciers were so large that they extended beyond the Alpine valleys, and becoming confluent on this plain formed a great sheet of ice which terminated against the flanks of the Jura. It is therefore a natural inference that the glacial deposits

[1] Lockwood in Greely's "Three Years of Arctic Service."

now found on the plain were formed during this extension of the Swiss ice, but it is a curious fact that English geologists have paid very little attention to them. No one, so far as the author is aware, has compared these clays with the British boulder-clays with the view of indicating points of difference or resemblance; nor have these Swiss clays been brought forward as a special proof of the capacity of glaciers to form boulder-clay. Professor Bonney, however, informs the writer that he thinks they may fairly be regarded as proof that land-ice can make a boulder-clay, or rather that a boulder-clay can result from the extension of land-ice, but that there is little evidence to show how the clay has been formed. The general moundiness of the surface of the deposits suggests, however, that they have been formed during the retreat and melting of the ice rather than underneath the advancing mass of ice.

It should be remembered too that in most countries where glaciers now exist they are only remnants of much larger glaciers, which may have long ago swept the valleys clear of all loose débris and surface deposits. It may be, therefore, that the material of *glacier-formed* boulder-clay is gathered by advancing glaciers, accumulated during many centuries, and only finally arranged by the receding ice. In a future chapter we shall see that boulder clay can also be formed in a very different way.

CHAPTER XIII.

LACUSTRINE DEPOSITS.

THE various ways in which lakes have originated will be discussed in a later part of this volume. For our present purpose they may be classified under two heads,—(1) Freshwater Lakes; (2) Saline Lakes. Freshwater lakes always have rivers flowing out of them as well as into them, and they can therefore be viewed as merely deep and wide portions of the river-course where the current is checked and much sediment deposited. Saline lakes never have excurrent rivers, for they only become saline when the quantity of water running into them is less than that evaporated from their surface.

§ 1. *Deposits in Freshwater Lakes.*

1. **Mechanical Deposits.**—Where rivers enter lakes, deltas similar to those described in the last chapter will be formed, but these will generally consist of more varied materials; because rivers flowing into lakes usually run with greater velocity than when they enter the sea, and are more liable to floods which sweep down a quantity of coarse débris; thus boulders, gravel, and sand, are either continually or occasionally poured into lakes, besides the finer sediment which rivers everywhere carry.

The detritus thus brought down from the surrounding land is arranged in a definite and peculiar manner, as may be seen by watching any small stream which enters a pool. The particles of sand and gravel swept along by the stream are dropped when they enter the pool or lake, and are spread out in a fan-shaped deposit, the surface of which is

nearly level or gently inclined, ending in a steeper slope (see fig. 61). The inclination of this slope varies with the coarseness of the materials. Further supplies of débris are pushed along the level surface and shot over the edge of the bank so as to form an additional sloping layer, and so the process goes on, successive layers being deposited, sometimes of gravel, sometimes of sand, but all sloping in the same direction, viz., away from the mouth of the stream.

All this time, however, the river is also pouring into the lake a quantity of finer sediment which is carried out far beyond the edge of the delta. The turbid waters of the river, having a greater specific gravity than the clearer waters of the lake, sink beneath the latter and often steal along the bottom for a considerable distance before they part with their burden of suspended sediment. As De la

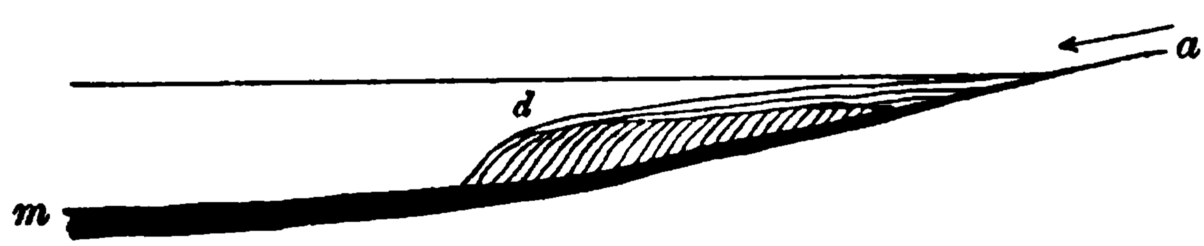

Fig. 61. Diagram of a small Delta in a Lake.
m, mud spread on lake floor. *d*, delta deposit.

Beche remarks, "if a long trough be filled with clean water, and turbid water be very quietly poured into it at one end, the mode in which the latter finds its way beneath the former will be at once seen." The fine mud, therefore, which is carried onward by the current of the river, will be evenly spread over the bottom of the lake in advance of the growing delta.

Besides a large river, there may be other smaller streams and torrents flowing into the lake, and each of these will form a small delta and contribute its share of detritus, so that in course of time the lake may be completely filled up by the growth of delta deposits.

Fig. 61 may be taken to represent a small delta formed by a stream coming from the direction *a*, and resting upon a stratum of fine mud, *m*, which has been spread over the lake floor by the current of the main river. The deposits

being coarse the slope of the delta is steep. Sir Charles Lyell states that the subaqueous slope of a minor delta in the Lake of Geneva is four times as steep as that of the main delta at the head of the lake.

The deposits of the river Rhone in Lake Geneva probably consist of numerous alternations of fine gravel, coarse and fine sand, silt and mud; for during the summer when the snows melt the volume and velocity of the river are greatest, and large quantities of sand, mud, and vegetable matter are introduced, but during the rest of the year the influx is so much less that, according to Saussure, the whole lake stands six feet lower.[1]

The river Rhone is thus gradually filling up the lake, and has already formed a flat alluvial plain sixteen miles long at its upper end. An ancient town called Port Vallais (Portus Valesiæ) stood on the water's edge about 900 years ago, but now it is a mile and a half inland, so much new ground having been formed in the interval. It would be quite possible to calculate the time required for the river to convert the whole lake into a similar plain, through which it would then meander to its present outlet at Geneva.

Sir Charles Lyell tells us that many such filled-up lakes may be found in the course of the Rhone and its tributaries. "If we ascend, for example, the valley through which the Dranse flows, we find that it consists of a succession of basins, one above the other, in each of which there is a wide expanse of flat alluvial lands, separated from the next basin by a rocky gorge, once perhaps the barrier of a lake."[2]

In our own country a good instance of such an obliterated lake occurs at Rossthwaite above Borrowdale, and there are many in Scotland, where they are known by the name of *lochlands*.

In the case of large lakes which are not traversed by any large river, the deposits are rather different. Lake Superior is the largest expanse of fresh water in the world, and numerous rivers run into it, but none form any considerable delta; round its shores there are beaches of sand and

[1] Lyell's "Principles of Geology," tenth edition, vol. i. p. 418.
[2] *Ibid.*, vol. i. p. 419.

shingle, and its bottom consists generally of a very adhesive clay containing shells of the species now living in the lake. "When exposed to the air, this clay immediately becomes so indurated as to require a smart blow of the hammer to break it. It effervesces slightly with diluted nitric acid, and is of different colours in different parts of the lake; in one district blue, in another red, and in a third white, hardening into a substance resembling pipe-clay."[1]

2. **Deposits of Organic Debris.** — *Carbonaceous.*— Interstratified with the mechanical accumulations just described there will generally be some which are chiefly formed of organic remains. At times and seasons when much vegetable matter is carried into the lake, this is spread out and embodied with the mud or sand, giving rise to a black carbonaceous or lignitiferous deposit.

The quantity of driftwood carried by rivers which traverse a forest-covered country is sometimes very great, and when this is arrested by a lake large deposits of lignite may be formed. The Mackenzie River in North Canada in its periodical floods sweeps through the pine forests which border its banks and carries away thousands of trees every year. Many of these sink in the eddies of the river and form shoals, which gradually grow into islands. A thicket of small willows covers the new-formed island as soon as it appears above water, and their long fibrous roots serve to bind the whole firmly together. When such islands are subsequently cut into by the river, they show alternating beds of lignite, clay, and sand, the tree trunks having decayed into the blackish brown substance known as *lignite*, or wood-coal.

Dr. Richardson, from whose account the above is condensed,[2] says: "It was in the river only that we could observe sections of these deposits, but the same operation goes on on a much more magnificent scale in the lakes. A shoal of many miles in extent is formed on the south side of Athabasca Lake by the drift-timber and vegetable débris brought down by the Elk River, and the Slave Lake

[1] Lyell, *op. cit.*, vol. ii. p. 422.

[2] "Geognostical Observations on Capt. Franklin's Polar Expedition."

itself must in process of time be filled up by the matters daily conveyed into it by the Slave River. Vast quantities of drift-timber are buried under the sand at the mouth of the river, and enormous piles of it are accumulated on the shores of every part of the lake."

Calcareous.—In lakes which are fed by springs or by small streams that do not carry much muddy sediment, other deposits of organic origin are formed. In such lakes freshwater shells abound, and their dead shells often accumulate in such quantity as to form thick layers of what is called *shell-marl.* Similar beds are sometimes formed by the bivalve shells or carapaces of the small crustacea called *Cyprides*, which often swarm in such pools and lakes. Lastly, the pond-weed called *Chara* secretes so much carbonate of lime in its stalks, leaves, and fruit, that the whole plant has a stiff and solid aspect; it forms tangled masses which gradually decay into a layer of calcareous matter very like tufa.

Such deposits have been exposed to view by the drainage of small lakes and meres, the marl being useful for agricultural purposes. Sir Charles Lyell states that the marl in the Scotch lakes is almost entirely composed of the shells of mollusca, chiefly *Limnæa, Planorbis, Valvata,* and *Cyclas*, some of them being in a decomposed and pulverulent state, and some retaining their original form.[1] *Cyprides* and the remains of *Chara* are also intermixed, and the whole is compressed into a marl which splits up into thin layers.

Lyell observes that the inflowing waters must bring a constant and copious supply of calcareous matter, otherwise no tufa or shell-marl is formed. All the Forfarshire marls occur in lakes which are supplied by springs containing carbonic acid and carbonate of lime; but round Loch Fithie there are no springs, and in it there is no marl, though it is surrounded by such deposits, and in every other respect the site is favourable to the accumulation of shell-bearing animals. The *Charæ*, too, are most calcareous in waters free from mud and strongly impregnated with lime.

[1] "Principles of Geology," vol. ii. p. 565.

Large deposits of marl are found in the old meres of the Cambridgeshire Fens, and Mr. S. B. J. Skertchly attributes their formation principally to the decay of *Charæ*, which still abound in the neighbouring dykes.[1] Shells form, however, a considerable portion of the mass, and there are occasional lines of peaty matter. An analysis of the marl in Whittlesey Mere showed that, after subtracting the moisture and organic matter (chiefly due to peat), 87 per cent. of the residue was pure carbonate of lime, 7 per cent. was an admixture of sandy matter, and the remaining 6 per cent. consisted of sulphate of lime, oxides of iron and alumina, and carbonate of magnesia in very small quantities.

A small lake in New Jersey, called Milk Pond, is described as being entirely surrounded by a thick deposit of shell-marl, which seems to cover the whole basin of the lake. It is perfectly white, and is mainly composed of bleached shells, and its thickness is known to be more than twelve feet.

Siliceous.—Deposits, consisting largely of silica, are formed in some lakes by the agency of minute vegetable organisms called Diatoms, which are able to secrete and appropriate the silica dissolved in the water, just as the molluscs secrete the carbonate of lime to form their shells. Diatoms consist of simple cells, either single, or united in a linear series, and each is enclosed in a siliceous case or shell; these cases are often elegant in shape and delicately sculptured on the surface. They are only visible under the microscope, but compensate for their minuteness by their extraordinary abundance, being so prolific that the number of individuals derived from a single diatom in one month would form a bed of silica, 25 square miles in extent and 20 inches thick (Ehrenberg).

Diatoms are found in the sea, as well as in bogs, stagnant pools and lakes, and thick deposits are sometimes formed by the accumulation of their siliceous cases, or frustules. Such is the berg-mehl (or mountain-meal) on the shores of certain lakes in Sweden. This is of such a fine, floury consistency that the inhabitants use it to mix with flour. Diatom-earth is also used to make dynamite

[1] "Geology of the Fenland," Geol. Surv., p. 60.

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It is known locally as *polierschiefer*, being used by lapidaries for polishing purposes. Similar stone found in Italy and elsewhere is called *Tripoli*.

Ferruginous. The substance known as Bog-iron-ore was also shown by Ehrenberg to be in some cases the product of a particular Diatom called *Gallionella ferruginea*, which forms long threads or filaments consisting of a series of minute cells. Professor Bailey thus describes their appearance in the pools near West Point, United States:— "The bottoms of these are literally covered in the first warm days of spring with a ferruginous-coloured mucous matter about a quarter of an inch thick, which, on examination by the microscope, proves to be filled with millions of these exquisitely beautiful siliceous bodies. Every submerged stone, twig, and spear of grass is enveloped by

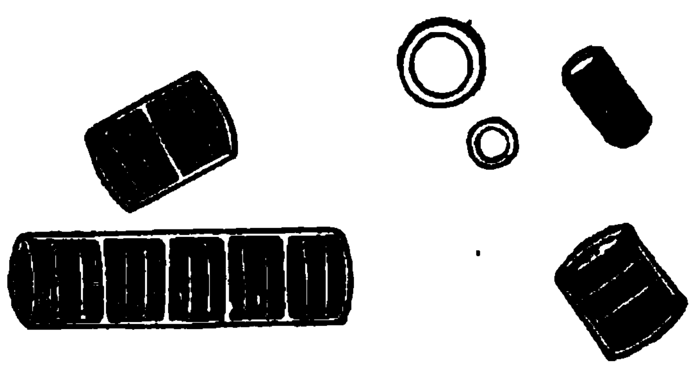

Fig. 63. Gallionellæ (highly magnified).

them; and the waving plume-like appearance of a filamentous body, covered in this manner, is often extremely elegant."

3. **Chemical Deposits.**—Deposits due to chemical precipitation are not common in freshwater lakes, but some ferruginous deposits have been formed in this way, especially in lakes which are fed by streams that rise on boggy uplands or forest-covered mountains. The rocks of such regions often consist of minerals that contain iron, so that there is much iron in the soil, and this is taken up by the organic acids to form humic and crenic salts that are carried away in solution. When the water containing them reaches the lakes, and is exposed to oxidation and evaporation, the iron is precipitated as a hydrous peroxide, and forms a deposit of soft brown iron ore (limonite) on the lake-bottom. This occurs in several lakes in Sweden

and Canada, and the ore is periodically raked up from the bottom for commercial use. In Sweden the deposit varies in thickness from 8 to 25 inches, and when removed it is said to be renewed by the process above described in about twenty-five years.

Carbonate of lime seems to be chemically deposited in some Irish lakes, in the form of a white, mealy substance, which is thus described by Mr. Jukes:[1] "The beds of the lakes in the limestone district of Ireland have often a thick deposit of white mud, which, when dry, is almost like flour in appearance, and is wholly soluble in acids. It is full of undecomposed freshwater shells of ordinary living species, but does not itself disclose any trace of an organic origin. My friend, Dr. J. Barker, of Dublin, subjected some of it, at my request, to a careful microscopical examination, but could discover no trace of organic structure. Around lakes that have been partially drained, large deposits of this substance, several feet in thickness, may be seen; and, in sounding some of the lakes, I usually found the lead sank into and came up partially coated with this substance. One some parts of the shores of the lakes there are accumulations of small nodular concretionary-looking balls of about half-an-inch in diameter, which Dr. Allman, of Edinburgh, told me were a species of Nullipore."

§ 2. *Saline Lakes.*

The deposits formed in saline lakes are chiefly due to chemical precipitation of the mineral matters carried in solution by the rivers which run into them. These streams may of course also lay down deposits of sand and clay in the manner already described, but we have only now to consider the matters in solution.

Whether the lacustrine waters retain them in solution, depends upon the amount of evaporation to which they are subjected. The air is always absorbing vapour from broad surfaces of water, so that the water which flows out of a lake is always less than the amount which flows in. Some large lakes have no outlet, even though they are fed

[1] "Manual of Geology," third edition, p. 384.

by several streams, and sometimes the evaporation is greater than the supply, so that the waters are gradually shrinking in volume. In such cases it is evident that the proportion of matter in solution will rapidly increase, since only pure water is taken out; and when the solution becomes a saturated one, precipitation will commence, and chemically formed deposits will be formed.

The basin of the Great Salt Lake in Utah, U.S., affords an excellent instance of the gradual desiccation of a large body of water. The present lake is about 80 miles long with an average breadth of 30 miles, but Mr. Clarence King calculates that it had originally a length of about 300 miles, and an extreme width of 180 miles.[1] The old lake was probably at first filled with fresh water, but climatal changes diminishing the supply, evaporation prevailed and the area of the lake grew less and less; the salts were gradually concentrated and finally precipitated over part of the area.

It would appear that the first salt to be separated was carbonate of lime, for calcareous sands and large deposits of tufa are found on the uppermost terraces; while an analysis of the present water discloses the fact that none remains in solution, though large quantities are annually brought in by the rivers. The reason of this seems to be that the carbonate of lime is unable to remain in solution in the presence of alkaline salts, such as the chlorides and sulphates of soda and potash. It is, therefore, quickly precipitated. These alkaline salts are supplied by the numerous mineral springs in the vicinity.

The next salts deposited from the diminishing lake were probably some of the sulphates, and finally, when parts of its area were separated and further concentrated, deposits of sodium chloride were formed. On the desert plains round the lake desiccation products are found, which consist principally of chloride of sodium (86 per cent.) with sulphate of lime (9 per cent.), and small quantities of the sulphates of soda and magnesia. In Nevada there is a salt-field formed by the evaporation of a lake which at the

[1] "Exploration of the 40th Parallel," vol. i. p. 492. See also the account of the older lake area (Lake Bonneville) by Mr. Gilbert, Mon. U.S. Geol. Survey, vol. i.

period of its greatest saturation occupied a basin about 20 miles in length. It is now a solid field of white salt, covered with a thin layer of brine in the winter months which completely evaporates in the autumn. In the middle the deposit of solid salt is five feet thick, but towards the west shore this is overlaid by a fine saline mud, in which beautiful octohedral crystals of salt occur. The solid mass consists chiefly of sodium chloride (97 per cent.) with small quantities of carbonate and sulphate of soda.

The Caspian Sea and Lake Aral are also good examples of large water spaces which are gradually growing salter by a process of concentration. The water in the open part of the Caspian Sea is fresh because such enormous quantities of fresh water are poured into it by the Volga, Ural, and other rivers, but its volume is slowly diminishing; salt lagoons are formed round its shores, and the surrounding deserts are covered with a salt efflorescence. The salts in solution are the chlorides of sodium and magnesium, the sulphates of lime, soda, and magnesia, with small quantities of the carbonates of lime and magnesia. Before, however, the sodium chloride (rock-salt) can be deposited, it is necessary that more than nine-tenths of the bulk of water should be removed by evaporation, and until this saturation point is reached only small quantities of other salts will be deposited. When, however, the concentration has proceeded so far a large deposit of rock-salt will take place. Thus in the salt lakes about the mouth of the Volga, a compound of the sulphates of magnesia and soda, called Astrakanite, is formed in the winter when the evaporation is not great, while in summer, rapid evaporation causes the deposition of rock-salt.

The Sea of Aral is very salt, especially in the shallow water near its shores; and Lake Elton, a small lake in the desert north-east of the Caspian, shows a still greater state of concentration, its waters being intensely salt and bitter. Analysis shows them to contain 30 per cent. of solid matter, two-thirds of this being magnesium chloride, and the amount of sodium chloride being very small. This shows that the water is a kind of mother liquor from which the sodium chloride has been precipitated.

The water of the Dead Sea has a similar composition,

containing 26 per cent. of saline matter, of which 15 parts are magnesium chloride. This great lake is surrounded by lacustrine deposits, consisting of marls and shales with beds of rock-salt and gypsum, reaching to a height of 600 feet above the lake, and attesting its much greater size in former times. The cliffs of Jebel Usdum, at the south end of the sea, are described by Professor Hull, as consisting in the lower part of solid bluish rock-salt which is from 30 to 50 feet thick, and is capped by beds of marl, salt, and gypsum.[1]

Lakes fed by Mineral Springs.—We have hitherto only considered the chemical deposits produced by the evaporation and concentration of ordinary river waters when poured into lakes. But extensive deposits may be rapidly formed in lakes without great evaporation, if their waters are supplied by springs which contain a large amount of mineral matter in solution.

Such mineral springs are especially abundant in districts where volcanic action has been rife; they are often thermal, and generally impregnated with carbonic acid, so that they usually hold in solution large quantities of carbonate of lime. The carbonic acid escapes as a gas, and the calcareous matter is precipitated upon the lake-bottoms in the form of travertine.

In Sir C. Lyell's "Principles of Geology," a description is given of the lake of the Solfatara, between Rome and Tivoli.[2] This is fed by a stream of warm water proceeding from a smaller lake above; and the water is so saturated with carbonic acid, that the escape of the gas gives it the appearance of being in a state of ebullition. Tufa and travertine are formed in the lake at a very rapid rate. The principal buildings of ancient and modern Rome are built of travertine obtained from the quarries of Ponte Lucano in the same district, where there has evidently been a lake at some remote period in which this deposit has been formed.

Travertine derives its other name of Tibur-stone from the town of Tivoli (ancient Tibur), which stands on an

[1] "Mount Seir and Western Palestine," Richard Bentley and Son, 1885, p. 131.
[2] Vol. i. p. 404.

enormous mass of this rock. The walls of the chasm below the cascade of the river Anio disclose a magnificent section of tufa and travertine in horizontal beds for a depth of 400 or 500 feet. Lyell observes: "There can be little doubt that the whole of this deposit was formed in an extensive lake which existed at the close of the period of volcanic activity, by which the lavas and tuffs of the Roman territory were formed. The external configuration of the country has since been greatly changed, and the Anio now throws itself into a ravine excavated in the ancient travertine. Its waters give rise to masses of calcareous stone, scarcely, if at all, distinguishable from the older rock."

Lakes resulting from the Isolation of Sea-Water.—Whenever portions of sea-water are separated by any means from the open sea so as to form isolated lakes or lagoons, the solution quickly becomes concentrated by evaporation, and precipitation takes place.

Sea-water contains about 3½ per cent. of solid matter in solution, that is to say, every 100 parts of sea-water contain 96½ parts of pure water and 3½ of mineral matter. In water from the English Channel the actual amount is 3·525, and in the Mediterranean 3·765.

When the solid matter is dried and analyzed it is found to consist of certain salts in the following proportions: [1]

Chloride of sodium (common salt)	77·758
Chloride of magnesium	10·878
Sulphate of magnesia	4·737
Sulphate of lime	3·600
Sulphate of potash	2·465
Bromide of magnesium	·217
Carbonate of lime	·345
	100·000

The smallness of the quantity of carbonate of lime to be found in sea-water, compared with that in almost all rivers, is a point that will be discussed in a subsequent chapter.

Another substance occurring in minute proportions in

rofessor Dittmar, "'Challenger' Report

sea-water is silica. Forchhammer found it in all the specimens of sea-water which he analyzed, the mean proportion being 9 in 100,000 parts of water.

When a quantity of sea-water is isolated and evaporated the point of saturation for sulphate of lime is much sooner reached than that for chloride of sodium; the former requiring only 37 per cent. of the water to be removed, and the latter 93 per cent. Gypsum, therefore, must always be deposited before rock-salt, and it is possible for this deposition of gypsum to take place without the point of saturation for rock-salt being attained. This may be the reason why, though the sea contains twenty-one times as much sodium salt as it does gypsum, that the latter more frequently occurs as a mineral deposit than the former, though it is not often found in such massive beds.

A good instance of the formation of gypsum beds from the concentration of sea-water is described by Professor Dana, as occurring in the dried-up lagoon of a coral island called Jarvis Island in the Pacific Ocean.[1] The flat surface of the central basin is covered with a deposit of guano, and underlying this is a stratum of sulphate of lime, frequently 2 feet thick, resting upon a bed of coral, sand, and shells. This deposit of gypsum is probably to be explained by the gradual elevation of the island, during which the lagoon waters were partially evaporated, but replenished from time to time by an influx from the sea, so that for a long time the condensation was not sufficient to precipitate chloride of sodium. Eventually, however, the whole was dried up, and salt was deposited, for around the lowest portion of the basin are incrustations of gypsum and common salt, ripple marks, and similar evidences of the gradually disappearing lake. Much of the salt may have been washed out by rain. Similar deposits of gypsum occur on many other elevated lagoons among the Pacific islands.

A good instance of the production of rock-salt by the evaporation of sea-water is presented by the Bitter Lakes of the Isthmus of Suez. Before the construction of the Suez Canal the surface of these lagoons was far below the

[1] Dana's "Coral Reefs," 1875, p. 251.

level of the Red Sea, and the evaporation of their waters had produced a bank of salt 66,000,000 square metres (16,000 acres) in extent, composed of layers which were 5 to 25 centimetres (2 to 10 inches) in thickness. It would appear that the lakes had been inundated from time to time by the waters of the Red Sea, while in the intervals between these incursions the evaporation and concentration was sufficient to precipitate a layer of salt, and so in time the large deposit above mentioned was accumulated.

Similarly in the limans of Bessarabia, on the Black Sea, which dry up in summer, we have the formation of salt beds going on before our eyes.

One of the *salinas* of South America is thus described by Mr. Darwin:—"The mine consists of a hard stratum, between 2 and 3 feet thick, of the nitrate, mingled with a little of the sulphate of soda, and a good deal of common salt. It lies close beneath the surface, and follows for a length of 150 miles the margin of a grand basin or plain. This, from its outline, manifestly must once have been a lake, or more probably an inland arm of the sea, as may be inferred from the presence of iodic salts in the saline stratum. The surface of the plain is 3,300 feet above the Pacific."

CHAPTER XIV.

MARINE DEPOSITS.

IN describing the operations of a river, we have followed the course of the detritus transported by its current, and have seen, that though this is temporarily deposited at certain points along the river-valley, yet most of it is eventually moved on again and triturated into smaller and smaller particles. Sediment is thus continually brought down from higher to lower levels, and never finds a permanent resting-place until it is carried into a lake or into the sea. Even delta-mud is liable to removal, and from its mouth the river is constantly discharging a cloud of sediment, which is carried away by the tidal currents and spread over the sea-bottom.

Excepting, therefore, the small portion which is intercepted by lakes, the sea is the ultimate recipient of the materials carried down by rivers. To this is added the detritus which the sea-waves erode from the coast, and the whole is carried by the marine currents till circumstances determine its deposition. Some of it is carried along the coast and sorted by the action of waves and currents till it is thrown up and deposited in bays and inlets. The rest of it is carried out to sea, and dropped at a greater or less distance from land, according to the fineness of the sediment and the strength of the tidal current, but it is only the very finest material which is carried more than 100 miles from land.

We must also remember that besides this visible sediment there is much invisible material dissolved in the water, and that this latter also is poured into the sea.

The lime is used by millions of marine creatures in building up their shells or stony structures, and the silica is used in the same way by certain lowly animals and plants. On the death of these organisms the hard parts

remain and accumulate, either on the sea-floor or against its margins. Corals, Mollusca, and Echmoderms are the limestone builders of the present day as they have been in all past time, and it is essential that the student should form an accurate conception of the conditions under which such rocks have been formed. For the purpose of making the account of these as clear as possible we shall describe the deposits under the following heads:—

1. Shallow-water Deposits . .	A. terrigenous. B. organic.
2. Deep-water Deposits . . .	A. terrigenous. B. organic.

1. *Shallow-Water Deposits.*

In the present chapter shallow-water deposits formed of inorganic current-borne detritus derived from the waste of the land will alone be considered.

Assortment of Material.—Let us commence with the case of a simple coast-line like that of the north coast of Spain, bordering the Bay of Biscay, or that of the west coast of South America, where for many hundred miles no large rivers enter the sea, and where the conditions of deposit are consequently reduced to their simplest form. On such coasts the short and rapid torrents from the mountains carry material to the sea, and the waves quarry more from the cliffs, and these are regularly sorted by the tidal currents. Thus for *several thousand miles* along the coasts of Peru and Chili, there is a perpetual rolling of shingle along the shore, parts of which are incessantly reduced to the finest mud by the waves and swept out into deep water by the tides and currents. Off this coast are successive deposits of shingle, sand, and mud, disposed in regular longitudinal bands, the coarser portions always nearest to the shore, and the finer sediment furthest away from it.

The same is the case along the eastern coast of Patagonia, and the soundings taken between Santa Cruz and the Falkland Islands in H.M.S. "Beagle," are mentioned by Mr. Darwin[1] as a good instance of this assortment of

[1] "Voyage of the 'Beagle,' 1876."

material, the size of the stones decreasing regularly with the distance from shore:—

Miles from shore.	Depth in fathoms.	Size of material.
2 to 4	11 to 12	Pebbles as large as walnuts with others of smaller size intermixed.
4 to 7	17 to 19	Pebbles about the size of hazel nuts.
10 to 11	23 to 25	Pebbles about the size of peas.
12	30 to 40	Pebbles $\frac{3}{16}$ of an inch diameter.
22 to 150	45 to 65	Coarse to fine sand.

Let us next take the case of a small river with a rapid current carrying detritus of all sorts, from small stones and pebbles to fine mud, according to the volume of water, and discharging them into a sea where there is no strong cross-current. As the river enters the sea it will first de-

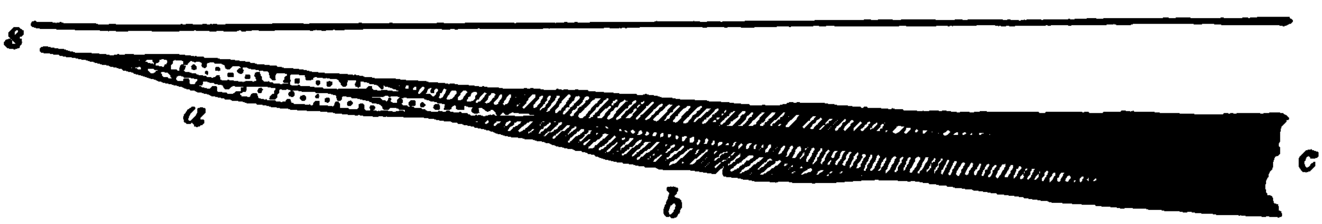

Fig. 64. Lenticular Deposits on a Sea-bottom.
s, *s*, the surface of the sea. *a*, pebble-beds. *b*, sand. *c*, mud.

posit the pebbles, next the smaller stones and coarse sand, farther out fine sand, and last of all, silt and mud. This order of succession is always maintained except where interrupted by local currents and influences. The width and extent of these deposits will, however, vary from time to time; when a river is in flood the coarser materials will be carried out to a greater distance, so that pebbles and shingle will be deposited over a tract of sand, and sand will invade the region of mud: again, when the river is low, clay or mud will settle down nearer shore, as it did before the flood-time, and cover up the outer beds of sand. In this way wedge-shaped or lenticular deposits of the various materials will be formed and interbedded with each other, as indicated diagrammatically in fig. 64.

There will be a further assortment of material according to the differences in the shape and specific gravity of the particles composing the muddy sediment. This subject

has been investigated by Mr. Babbage, who supposes the case of a river, the mouth of which is 100 feet deep (and a current of 2 miles per hour), delivering four varieties of fine detritus into a sea which has a uniform depth of 1,000 feet (166 fathoms) over a great extent, which sea is traversed by an ocean current moving in the same direction and with the same velocity.

He takes for granted that the four varieties of sediment are such as, from their size, shape, and specific gravity, would fall through still water, the first ·10 feet per hour, the second 8 feet, the third 5 feet, and the fourth 4 feet. The combined effect of the downward motion of the detritus and the onward motion of the water, would then bring the first variety to the bottom of the sea, at a distance of 180 miles from the river's mouth, and strew it over a space 20 miles long; the second variety would only begin to reach the bottom 225 miles from the river's mouth, and would be spread over 25 miles, and so on, as in the following table:—

No.	Velocity of fall per hour.	Nearest distance of deposit to river mouth.	Length of deposit.	Greatest distance of deposit from river mouth.
	Feet.	Miles.	Miles.	Miles.
1	10	180	20	200
2	8	225	25	250
3	5	360	40	400
4	4	450	50	500

We should thus have, proceeding from the same river, and poured into the sea either simultaneously or at different times, four different and widely separated patches of mud or clay on the sea-bottom.

It must not be supposed, however, that all the detritus poured into the sea by rivers, or obtained by coast-erosion, is distributed in this regular manner. The sea-shore is not always bordered by a shingle-beach, neither is the finer sediment invariably carried out to a distance from land.

Many rivers never carry anything coarser than sand or silt into the sea, even when floods have occurred in the higher parts of their valleys. Other rivers terminate in estuaries, where they only deposit the finest mud. Again, the materials derived from the erosion of cliffs are often carried laterally along the shore to great distances; the set of the currents varies with the height of the tide, and sometimes an undercurrent will set in one direction, while there is an overflow in a different direction, so that much even of the finer sediment may be carried along the shore and deposited where the currents slacken in bays or inlets.

Thus there are tracts along every coast-line where the land is gaining upon the sea in consequence of the restoration of some of the material which has been torn from it elsewhere. Shingle-beaches, river-bars, and sand-banks are being formed along shores which do not supply the material of which these deposits are composed, sheltered bays and estuaries are being silted up with materials introduced by marine currents, and the overplus of sand thrown up by the waves is often blown by the wind into sand hills which serve to protect the newly formed and low lying land from the effects of storms and high tides.

Shingle Beaches.—We have seen that the coarser portions of the débris won from the land are generally left or washed up on the shore near high-water mark, and form the shingles or pebble-beaches of which mention has already been made.

Attention to the changes of a shingle-beach will soon show that besides the moving of the stones backwards and forwards with every tide there is also a general lateral movement along the shore. This is due to the set or inclination given to the waves by the prevalent winds and currents; the breakers thus come to have a slightly oblique action; they do not drop a pebble exactly where they picked it up, but are constantly shifting the pebbles a little further on in one direction. The beach, therefore, considered as a whole, may be said to travel in that direction, until it is arrested by some point of land, or by some artificially constructed barrier.

It is possible also for stones and pebbles to be carried in various directions through the mediation of sea-weeds.

Mr. G. H. Kinahan[1] has observed certain beaches on the Galway coast, where very large rounded stones occur, and found that the quantity of these was increased after storms, and that some of the stones must have travelled through water of 15 fathoms in order to reach the beaches. On investigation he discovered that similar stones were scattered over the sandy bottom of the sea outside, and that laminaria and other sea-weeds grew luxuriantly on them, often having fronds 20 feet long. These fronds made the stones so buoyant, and gave such a surface for waves and currents to act on, that though unmoved in calm weather they were transported landwards during storms, and were eventually thrown up on the beach, where the weeds decayed and the stones were added to the shingle.

On the east coast of England sand and shingle travel from north to south, because a strong current sweeps southward along the shore. On the south coast beaches travel eastward, in consequence of the prevalent winds and strongest currents both setting from the S.W. If a pier or groin be erected anywhere on this coast a bank of shingle will be gradually accumulated on its western side. Long shingle beaches are formed at certain points, and nearly all the pebbles composing them have been obtained from the cliffs and shores to the westward of that place.

The Chesil Bank, on the coast of Dorset, is a good instance of such a beach. It commences near Burton Bradstock, and extends as far as the Isle of Portland, a distance of 17 miles. For the first 5 miles it is banked against the shore; from Abbotsbury onwards there is a narrow channel or estuary, called the Fleet, on its inner side, this section of its length having a height of 20 to 30 feet above high-water mark, and a breadth of about 500 feet. The last 5 miles form a bar or isthmus connecting the Isle of Portland with the mainland, and at the S.E. end of this, its height is 40 feet and its breadth about 600 feet. It is a remarkable fact, that although the pebbles composing the beach have all come from the westward, those at the N.W.

[1] "Proc. Roy. Irish Ac.," 2nd Ser. vol. iii. p. 202.

end are very small, and they gradually increase in size towards the S.E. The reason of this is probably to be found in the greater size of the waves which break upon the south-eastern end, while nearer the head of the bay the waters are quieter and more protected from storms. The larger waves throw up the larger stones, and thus the material coming from the west is sorted according to size and weight along the whole length of the Bank.

Hurst Castle Bank is another good example of a shingle-beach. This juts out from the Hampshire coast, across the western entrance of the Solent, thus forming a bar which is about two miles long, 70 yards broad, and 12 feet high. It consists of rounded flints derived from the waste of the gravel-capped cliffs to the westward.[1] Other beaches formed in the same way of material coming from the west occur at Eastbourne and Dungeness.

Sand-flats and Sand-banks.—Along all the more open parts of a coast-line sand is generally accumulated; where there is a shingle beach the sand forms a flat below it, and is only exposed at low water, but where there is no shingle it forms the foreshore also, being driven up into ridges by the storm-waves, and often blown into sand-hills by the wind (see p. 200).

Open bays are favourable situations for the accumulation of sand, the material being brought into the bay by the tidal current and dropped at high tide, while the ebb flow in many cases only carries back the finer sediment and leaves the sand above low-tide level. This sorting action is assisted by the waves, which keep the surface of the sand-flat in a state of constant oscillation, both during the rising and falling of the tide. During storms and high winds this wave-action extends to deeper water, as is proved by the casting up of molluscs and other animals which are known to live on the bottom in moderate depths. Wherever tidal currents act strongly they keep the materials on the bottom in a state of movement, but where they spread over wide and shallow surfaces these materials accumulate to a greater or less extent. It is in this way that the floors of so many of our bays are paved with sand.

[1] Lyell's "Principles of Geology," vol. i. p. 531.

Morecambe Bay on the Lancashire coast is a good example of a bay which is being gradually filled up with sand; in this case the sand is supplied partly by the rivers flowing into the bay (the Lune, the Kent, and the Leven), and partly by the flood-tide entering the bay, by which the whole supply is distributed. Including the Lancaster and Fleetwood Sands, there are about 160 square miles of sand and silt exposed at low water over this tract. The depth of the deposit is unknown, but is probably at least 40 or 50 feet in many places. Shifting quicksands occur within it, in which a coach and horses have been swallowed up.

As a case of accumulation under different conditions we may mention the sands at the mouth of the Thames. The material for these has been brought entirely by the tidal currents, and is probably derived from the waste of the Norfolk and Suffolk coasts. Part of it is arrayed at the mouth of the estuary in long sand-banks, with deep channels between them, but a great quantity is thrown up on the Essex coast, where it forms the large sand-flats known as the Maplin and Foulness Sands, of which an area of about 40 square miles is exposed at low water.

With regard to the depth of sand on these banks, Mr. T. H. Tizard [1] says "it is probable they are upwards of 60 feet thick, for channels of that depth have opened out across the sands and again closed up, so that the bank has been dry at low water where 60 feet formerly existed; and the Goodwin Sands in the Downs, which have been bored, proved to be 80 feet thick."

The sands of Pegwell Bay, between Sandwich and Ramsgate, are another good instance of sands carried and deposited entirely by marine currents. In this case the sand travels from the south, and is washed up into the bay which is formed by the projecting cliffs of the Isle of Thanet.

Silt and Mud-flats.—These appear to be formed in two ways. Some are due to the formation of shingle beaches or sand-bars across the mouth of an estuary, causing the water inside to spread over a wide area, in which the sediment brought down by the river and that brought in by

[1] "Nature," April, 1890, p. 539.

the tide is spread out. The marshes of the Yare have been formed in this way.

"In the time of the Saxons the valley of the Yare was a great estuary, and extended as far as Norwich, which city is represented, even in the thirteenth and fourteenth centuries, as 'situated on the banks of an arm of the sea.' The sands whereon Yarmouth is built, first became firm and habitable ground about the year 1008, from which time a line of dunes has gradually increased in height and breadth, stretching across the whole entrance of the ancient estuary, and obstructing the ingress of the tides so completely, that they are only admitted by the narrow passage which the river keeps open, and which has gradually shifted several miles to the south."

"By the exclusion of the sea, thousands of acres in the interior have become cultivated lands; and, exclusive of smaller pools, upwards of sixty fresh-water lakes have been formed, varying in depth from 15 to 30 feet, and in extent from 1 acre to 1,200. The Yare, and other rivers, frequently communicate with these sheets of water; and thus they are liable to be filled up gradually with lacustrine and fluviatile deposits, and to be converted into land covered with forests."[1]

Other marshes and mud-flats are formed off open shores entirely by material brought in from the sea; the conditions being apparently such as will cause the current setting along the coast to slacken gradually, so that it first drops the sand, and is only able to carry fine sediment shoreward over the sand-flats. This process can be watched in operation along the shores of the Wash. The strong current from the north brings sand and silt into the bay of the Wash, and the waters of every tide bear along a certain amount both of the coarser and finer material. The former is naturally deposited before the latter, and forms sand-banks and sandy flats which extend up to the limits of ordinary high-water mark, but are constantly varying in their position and conformation. Inside these sand-flats, are mud- or silt-flats which are only covered at spring-tides. When the water reaches these higher flats, the force of the

[1] Lyell's "Principles of Geology," vol. i. pp. 516, 517.

tide is slackening, and the current is never strong: the muddy waters slowly spread over the nearly level surface, and much of the sediment which they carry is deposited during the slack of the tide. This deposit remains where it rests, for the slight movement of the ebb is not sufficient to disturb it, although it is capable of carrying away such sediment as remains in suspension.

The tract of shore, therefore, which lies between the high-water marks of ordinary tides and spring-tides, is slowly raised by the thin sheet of mud which is spread over it at every spring-tide; every such sheet or layer forms a separate lamina, and the whole accumulation is a deposit of laminated silt.

When the surface of the flat has thus been raised to a certain height, the glass-wort (*Salicorina herbacea*), locally known as the samphire, begins to grow upon it, and facilitates the further deposition of silt, which now rapidly accumulates. The surface becomes gradually covered with sea-thrift and other marsh-plants, and passes into the condition of "green marsh," which is only overflowed at very high spring-tides. Mr. Skertchly observes that the "samphire marsh" is always distinguished from that which, having become covered with verdure, is called "green marsh"; also that the two tracts occupy different levels, the samphire marsh being only 8·6 feet above Ordnance datum, and the green marsh averaging 11 feet above the same datum.

The Marsh-land of East Lincolnshire, which extends from the mouth of the Humber to the Wash southward for a distance of 35 miles, with an average width of 3 to 4 miles, has been formed in the manner above described. Beds of peat containing branches and trunks of trees are interbedded with the marine silts and clays, and mark periods when deposition was interrupted; but the series is essentially marine, and is from 30 to 40 feet thick near the coast. The sediment of which it is composed has been derived partly from the erosion of the coast of Holderness, and partly from the supply brought down by the Humber. The Marsh-land is not now being added to except at and north of Saltfleet, while the southern part of it from Mablethorpe to Wainfleet was once more extensive than

it is now, having at various times been reduced by inroads of the sea.

The Marsh-land passes southwards into the wide level of the Fen-land, which is not a delta (as sometimes stated), but a silted-up bay. The silts and clays of the Fens are not fluviatile, but marine deposits; they are a continuation of the marsh beds, and have been formed in the way above described. Mr. Skertchly states[1] that in some places a breadth of 3 miles of land has been formed since the Roman occupation, and that the process is now going on. About 55 square miles were thus added to England between the second and seventeenth centuries, *i.e.* in 1,500 years; assuming, therefore, that the rest of the Fen-land has been accumulated at the same rate, and estimating the area of silt and clay land at 550 square miles, the time occupied in its formation will have been 15,000 years.

Silting up of Bays on the South Coast.—It would be easy to indicate the tracts along the eastern and southern coasts of England where similar additions have been made to the land, just as in Chapter X. we mentioned those places where land had been lost by the action of the sea; but it would occupy too much space to describe all these in detail, and it will suffice to mention a few of the more notable instances of accretion that occur on the south coast.

The first of these is the union of the Isle of Thanet to Kent in historic times. "The isle of Thanet was, in the time of the Romans, separated from the rest of Kent by a navigable channel, through which the Roman fleets sailed on their way to and from London. Bede describes this small estuary as being, in the beginning of the eighth century, three furlongs in breadth; and it is supposed that it began to grow shallow about the period of the Norman Conquest. It was so far silted up in the year 1345, that an Act was obtained to build a bridge across it; and it has since become marsh-land, with small streams running through it.

This silted-up channel widens out eastward into a tract of marsh-land which extends along the border of Pegwell

[1] "Geology of the Fenland," Mem. Geol. Surv., pp. 9, 182.

Bay from Minster to Deal. It is in fact a silted-up portion of that bay, and the old Roman port of Ritupium is now a mile and a half from the shore.

The rich level tract called Romney Marsh, lying between Hythe and Hastings, is the site of a silted-up bay; measured along the coast, its frontage is about 25 miles in length, and its area is about 100 square miles. The sea is now excluded from the marsh, partly by natural barriers of blown sand and shingle, partly by artificial banks, but the greater part of its surface is below the level of high tide. The marine and estuarine deposits filling this tract are sometimes 70 feet deep, the lower part being always sand with marine shells, and only the upper 10 or 15 feet consisting of silt and clay with layers of peat. The marsh has received great accession within historic times. The town of Rye was once destroyed by the sea, but it is now two miles distant from it.

In Sussex, between Hastings and Eastbourne, there is a considerable area of marsh, which doubtless occupies the site of a silted-up bay. In Pevensey Level the general succession of deposits is—(1) Vegetable soil; (2) Clay, with fresh-water shells; (3) Clay, with marine shells.

The Lewes Levels, between Newhaven and Lewes, occupy the site of an estuary which had been silted up within the last 800 years. The usual succession of beds found here is described by Dr. Mantell as follows, the total depth being from 30 to 36 feet:—

1. A bed of peat 5 feet thick, enclosing trunks of trees.
2. Blue clay, containing fresh-water shells.
3. Blue clays, containing a mixture of fresh-water and marine shells.
4. Blue clay, with marine shells only, and skull of Narwhal.
5. At bottom a bed of white marly clay.

The contents of these deposits give the key to the whole history of their formation. The clay with marine shells indicates the period when the sea had free access to the valley; subsequently a shingle bar was formed across its mouth, blocking out the salt-water, and causing the formation of a marsh. The gradual change from salt to fresh-water conditions is plainly shown by the increasing

proportion of fresh-water products, till at length it became a land surface, and supported a thick growth of forest.[1]

Selsey, as its name implies, was once an island, and was separated from the mainland by a shallow estuary, the site of which is now occupied by Thorney Marshes and Pagham Harbour. The old historian Bede (A.D. 731), describes the place "as encompassed by the sea on all sides except the west, where is an entrance about the cast of a sling in width; which kind of place is by the Latins called a peninsula." By the time of the Conquest, however (A.D. 1060), it appears to have been completely joined to the mainland.

Poole Harbour, on the coast of Dorset, has been silted up in still more recent times. Mr. Brannon, who examined and reported on the harbour in 1859, has traced the following sequence of causes. He says: "As long as the sand cliffs to the east of the harbour stood southward of certain lines of bearing with the Isle of Purbeck, all the sand worn from them was carried out to sea and deposited in the Channel. So soon, however, as these cliffs had been cut back within these lines of bearing, the ebb currents formed an eddy outside the harbour, and in it some of the sand was deposited. This sand-bank (the Hook Sand) does not appear to have existed before the reign of Henry VIII., and when it had so increased as to rise above low-water mark, the wind drove up sand on to the shore, and sand-hills were formed across the mouth of the harbour, leaving only the present narrow entrance." He thinks the silting-up of the harbour began only about 200 years ago, but at first the changes were very slight, and were scarcely noticeable up to the end of the eighteenth century. The material is brought in from the Hook Sand by the tide, and since the beginning of this century the flood-tide has taken in very much more than the ebb carried out, and what was once a fine harbour is being rapidly converted into a marine marsh.[2]

Deposition increased by Depression.—It is evident that when any part of a bay, or estuary, is silted up to the level of high-water mark, no farther deposition can

[1] Mantell's "Wonders of Geology," seventh edition, p. 62.
[2] See "Geologist," vol. iii. p. 430.

take place over its surface: the material brought down by the streams is carried on and deposited outside that already accumulated, and so the newly-formed land increases by the addition of matter to its margins, as already explained in the case of deltas.

It is clear also that if the area of deposition is being raised, the silting-up will be accelerated, for the amount of matter deposited over any one spot will be less than if the area were stationary. On the contrary, if the whole area be permanently lowered a few feet, mud and silt will again be thrown down and will continue to accumulate until it raises the surface to the former level, and thus a greater amount of matter will be deposited over a given spot. Continued subsidence will allow of equally continued deposition, and in this manner the thickness of deposits may be indefinitely increased.

Deposits in Shallow Seas.—Much of the material gained from the land is carried seaward by the retiring tide and by the currents which set along the shores, and is eventually deposited at a greater or less distance from the land, according to the strength of the current and the fineness of the material.

The seas surrounding our own islands are exceptionally shallow, the North Sea being in few places more than 50 fathoms deep, and there are only two parts of the Irish Sea which reach that depth. From the deposits which are now being formed in these seas, we may obtain a good idea of the manner in which the materials worn from the surrounding shores are disposed over their bottoms. The Admiralty charts, like all other good charts, indicate by letters the nature of the bottom as well as the depth; and by colouring these charts with different colours, according as the bottom consists of sand or mud, we get a very instructive map of the deposits now being formed.

Sand is the prevalent deposit in all these shallow seas. Thus the floor of the North Sea may be described as a vast expanse of sand interrupted only by a few tracts of mud. The chief of these mud tracts is a rather large space to the north-east of Scotland, and beyond it there is an area of clayey bottom, which probably dates from the Glacial period, and is not a modern deposit. In the middle of the

North Sea, between Denmark and the Dogger Bank, there is a considerable area of muddy sand and silt, but this is entirely surrounded by sand.[1]

In the English Channel sand also predominates, but much of it is shell sand, which will be described under the head of organic deposits. There are some irregular tracts of gravel and shingle which occur at various depths, and most of them are probably ancient deposits formed under different geographical conditions than those which now prevail.[2] There are also several tracts of bare rock, evidently spaces swept clear of deposit by the strong currents which set in and out of the Channel.

Outside the mouth of the Channel there is a submarine plateau which extends for 200 miles west of Cornwall, and for the same distance south of Ireland, and is everywhere covered by less than 100 fathoms (600 feet) of water. Over the greater part of this large area sand of varying degrees of coarseness prevails, with here and there a patch of gravelly or stony bottom, and a few tracts of mud. One of these last lies off the mouth of the Bristol Channel, and about midway between Cornwall and Ireland, its existence apparently depending more on the influence of currents than on the depth of water. It is entirely surrounded by an irregular tract of fine sand and silt, which is prolonged eastwards toward the mouth of the Bristol Channel, and southward to encircle another tract of mud, which lies to the west of the Scilly Islands. The disposition of these deposits is represented on the map, fig. 65, the scale of which is about 30 miles to an inch.

There are one or two other small patches of mud and muddy sand, but all the outer part of the plateau, which is between 70 and 100 fathoms deep, has a bottom of sand and shelly sand. Such a distribution of material is an exception to the rule that the fineness of the sediment increases with the distance from land, and is evidently the outcome of some special conditions. We should have expected that at a certain distance from the shores of Ireland and Cornwall fine sand would everywhere be

[1] For details see Delesse, "Lithologie du Fond des Mers," Paris, 1872.

[2] See Godwin-Austen, "Quart. Journ. Geol. Soc.," vol. vi. p. 69.

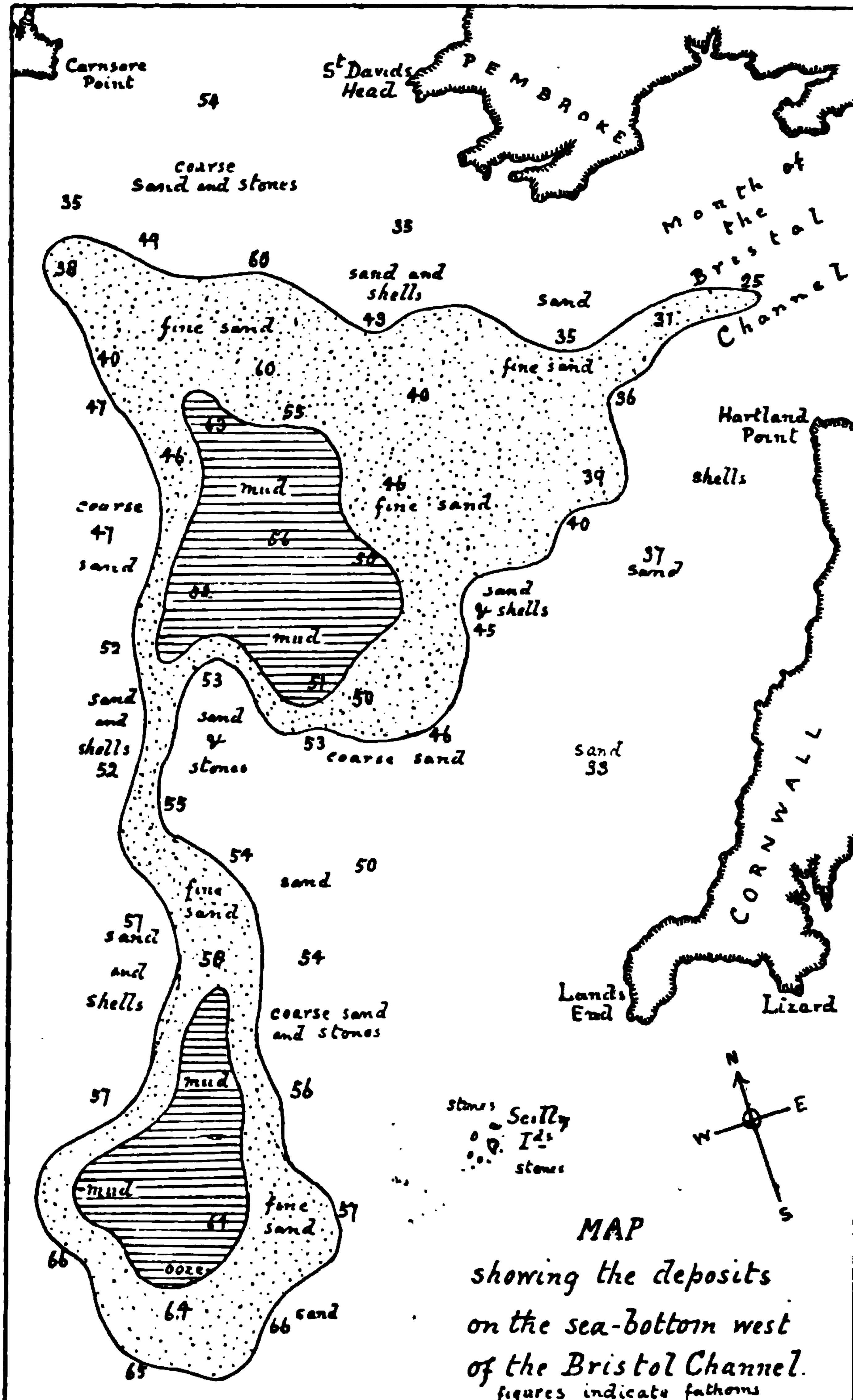

Fig. 65. Scale 32 miles to an inch.

found, that further out there would be mud, and that the mud would extend westward until it gradually passed into the deep-sea muds and oozes of the Atlantic, which will be described in the next chapter.

This, however, is not the case, and the anomaly may perhaps be accounted for partly by the peculiar contours of the sea-floor, and partly by the influence of waves of translation generated in the Atlantic, and affecting a great depth of water. Mr. A. Hunt has discussed this matter, and writes: "It seems highly probable that water displaced by wind pressure and atmospheric pressure over large areas in the Atlantic enters the Channel in the form of waves of translation, and there stirs up and places within the grasp of other currents all silty deposits light enough to be disturbed. Such removal of mud and silt would account for the sandy character of the bottom as evidenced by the charts."[1] The mud so sifted out would be redeposited nearer shore, and the two tracts in fig. 65 probably lie beneath areas where the surface currents have a tendency to circulate.

In the Irish Sea a large area of mud commences off the coast of Meath, and extends northward between co. Down and the Isle of Man for a distance of 60 miles, with an average width of 24 miles, giving an area of about 1,400 square miles of mud. It is surrounded by a narrow tract of muddy sand, which is prolonged northward through the North Channel, and north-eastward to the mouth of the Solway Firth. There is also a long tract of muddy sand off the coasts of Lancashire and Cumberland. Neither of these tracts depend much on the depth of water.

Returning to the plateau south of Ireland a narrow strip of sand runs northward, covering the shelving slope which lies between the south-west of Ireland and the 200 fathom line, and thence spreading out over a wide area of the sea-floor between Ireland and the Porcupine Bank, much of this area being less than 100 fathoms (600 feet), and all of it less than 200 fathoms. On the south side of this tract there is a deep submarine bay which is filled with fine sand and mud.

[1] "Denudation and Deposition by the Agency of Sea Waves," printed for private circulation, 1889, p. 27.

From the north of Ireland and outside the west coast of Scotland and the Hebrides sand largely prevails within the 200-fathom line, which lies at a distance of from 100 to 150 miles off the main coast. The sand is interrupted by small areas of mud, by larger tracts of shell sand, and by occasional patches of bare rock where strong currents have prevented the accumulation of deposit.

Besides the tracts of mud which have been noticed above there are some which are directly due to river currents, and lie opposite the river mouths; these, as Mr. Lebour has observed, may be termed *submarine deltas*.[1] That of the Thames forms a spread of sandy mud or silt in the shape of a triangle, the base of which runs from Margate to Buxey Sand, but is interrupted by sand-banks already mentioned. The delta of the Seine is very well marked, and consists of similar materials, but its widest part faces the sea, and its apex runs up the estuary: a difference due doubtless to the conformation of the coast. At the mouth of the Firth of Tay there are mud-banks which have been recognized by Mr. J. Geikie as the submarine delta of the Tay.[2] The Elbe also forms a clearly marked submarine delta of mud, which is spread over the sea-floor between its mouth and Heligoland, and covers an area of about 180 square miles, while on either side the bottom consists of sand. The shallower slopes on either side have a sandy bottom.

Limits of Terrigenous Deposits.—It is evident from Mr. Babbage's calculation, above quoted, that there is a limit to the outward extent of the deposits derived from the erosion of the land. Under the conditions assumed by him this would be at a distance of 500 miles from the shore, but these conditions nowhere exist, and the extension of such deposits is generally much less.

In the first place it is assumed that the ocean current which bears the river-borne detritus onward flows in the same direction as the river, viz., directly out to sea; but this can seldom be the case, for most marine currents, whether in seas or oceans, sweep along the coasts or set outwards in an oblique direction from the shore. Sedi-

[1] "Proc. Geol. Assoc.," vol. iv. p. 162.
[2] "The Great Ice Age," 1874, p. 520.

ment, therefore, which is carried by such currents will not reach so great a distance from land as 500 miles, for supposing that the current sets outward from the river's mouth at an angle of 45° with the trend of the shore, sediment carried 500 miles in a linear direction will only be 350 miles from land when deposited. Secondly, it is probable that such currents are superficial, and do not retain their surface velocity down to any great depth. The actual river-current is certainly superficial, and as soon as the sediment has sunk through that it will be carried by the marine currents, which may have a different velocity, and the set of which may be in any direction.

As a matter of fact, the disposition of the currents round continental coasts is such that terrigenous material is seldom carried to more than 150 or 200 miles from land. The exceptions are off the mouths of the largest rivers of the world, such as the Amazon, the Mississippi, the Indus, and the Ganges. Blue muds are found at great distances from land in the Arabian and Indian Seas, but they are of peculiar composition, and extend to great depths, so it will be more convenient to describe them under the head of deep-water deposits.

Marine Deposits due to the action of Ice.—In considering the manner in which the products of ice-erosion are deposited on the sea-bottom, it must be remembered that there are two distinct kinds of ice in the sea, viz., land-formed ice, and sea-formed ice. The first is delivered into the sea from the end of glaciers, the second is produced by the freezing of the sea itself along the coast. Both carry detritus, but since the conditions of the two cases differ, it is possible that the deposits resulting from their action differ also in some degree, though perhaps not so greatly as might at first sight appear probable. We shall, however, describe each case separately.

1. *Glaciers and Icebergs.*—In the regions of Arctic cold where the snow-line reaches the sea-level, the glaciers descend into the sea, and large masses of ice are constantly breaking off and floating away as icebergs. These bergs often carry stones and blocks of rock which are dropped on the sea-bottom as the mass of ice gradually melts away.

The glaciers of Greenland and Spitzbergen have already been described. Some of them are 2,000 feet thick, and terminate in high cliffs more than 200 feet in height, which sometimes continue like a wall for a distance of 50 or 60 miles in front of the land. From these cliffs gigantic icebergs are from time to time dislodged, often rising from 100 to 200 feet out of the sea, which involves a thickness of nine or ten times that amount below water.

We have seen that in the case of inland glaciers the rock-fragments which they bear along fall on to the terminal moraine, while the finer detritus is carried away from the locality altogether by the stream which issues from beneath the glacier. When, however, a glacier terminates in the sea, both these kinds of detritus are deposited together in the bay or fiord where the glacier ends.

Sub-glacial rivers occur beneath the inland ice-sheet of Greenland, just as they do beneath the Alpine glaciers, and along certain parts of the coast where the ice does not reach the sea, these streams burst out as turbid torrents from below the terminal wall of ice. So also do they escape beneath the glaciers which descend into the gulfs and fiords, and where the ice is protruded far into the sea, the muddy water is discharged at a depth considerably below the level of the water, and the fine powdery mud sinks to the bottom in a continuous cloud without being transported far from the spot.

At the same time the bergs broken off from the glacier will drop a large part of their freight of stones and boulders as they float away; much more débris of the same kind will be contributed by the periodical melting of the coast-ice; and all will be embedded in the mud which is thus being deposited on the sea-bottom.

Fig. 62 is intended to illustrate the termination of a glacier in the sea, *a* representing the glacier, *b* one of the bergs detached from it, and *c* a deposit of clay and stones on the sea-bottom.

2. *Coast-ice.*—The nature and action of coast-ice have been described on p. 184. It was there stated that the ice-foot becomes loaded with a great quantity of rock-débris, much falls on to its surface from the cliffs above, many stones and boulders are picked up from the shore to

which it is frozen. When summer comes the ice breaks off from the coast and floats away with its load of land-débris, drifting about in the bays and along the coast, but not often travelling very far out to sea. Sometimes the floes are driven upon the shore during storms, and packed to a height of 50 or 100 feet, sometimes they break up over comparatively deep water, and their freight of mud and stones is then scattered over the sea-bottom.

The deposits thus formed must be accumulated rapidly and continuously, the materials are very various and are dropped indiscriminately upon the sea-bottom, the portions already deposited are constantly disturbed by falling fragments, and frequently exposed to the impact and pressure of ice-floes; under these circumstances they are not likely to present the clear lines of stratification which

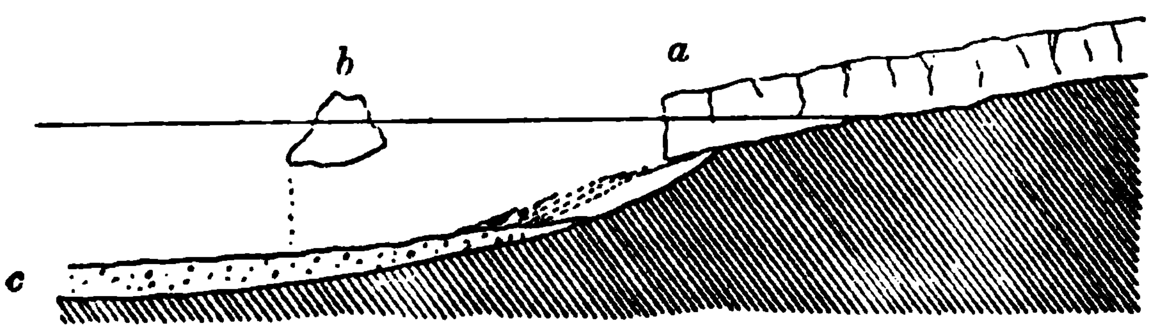

Fig. 66. Termination of a Glacier in the Sea.

other sediments slowly accumulated and sorted by current action always present.

Furthermore, this glacial deposit will not be confined to valleys, but will spread over the whole sea-bottom near the coast, and will cover all its irregularities.

It should be noted, too, that some of the boulders transported by coast-ice are carried to lower levels, and others to higher levels, the latter being especially the case if the whole coast is sinking. The ice-floes will then be driven further and further on to the land, bearing with them the stones and blocks derived from those parts of the shore which were previously exposed to their action, so that by this means rock-fragments may be carried upward in course of time to levels far above that from which they were originally detached.

Mr. Darwin long ago explained this transportal of

boulders from lower to higher levels on the hypothesis of a gradual submergence of the country while exposed to the action of coast-ice.[1] He remarks that fragments of rock "from being repeatedly caught in the ice and stranded with violence, and from being every summer exposed to common littoral action, will generally be much worn; and from being driven over rocky shoals, probably often scored. From the ice not being thick, they will, if not drifted out to sea, be landed in shallow places, and from the packing of the ice, be sometimes driven high up on the beach, or even left perched on ledges of rock."

During such submergence thick deposits of clay and stones must be formed, and will be subjected in many places to the friction and pressure of grounding bergs or of ice-sheets resting on the bottom. We may readily imagine, therefore, that in these localities compact boulder clays would be formed, while in other places the action of currents would sort the materials and arrange them in stratified beds.

We have actual testimony as to the processes now in operation on the north-east coast of Labrador, and the capacity of coast-ice to polish rock-surfaces, and to produce boulder clay. Professor H. Youle Hinde[2] has described the action of "pan-ice," which is formed by the breaking up of bay-ice, floes, and coast-ice during the storms of spring, and consists of large pieces or pans from 5 to 10 or 12 feet in thickness. "This broken ice is pressed on the coast by winds, and being pushed by the unfailing Arctic current, which brings down a constant supply of floe-ice, the pans rise over all the low-lying parts of the islands, grinding and polishing exposed shores, and removing with irresistible force every obstacle which opposes their progress. . . . During a period of subsidence the blocks of strata, boulders, mud, and sand, pushed to and fro on the shallow sea-bottom by pan-ice, ultimately accumulate in hollows below its action, and when the débris is pushed into profound submarine valleys such as exist on

[1] "Quart. Journ. Geol. Soc.," vol. iv. p. 315.

[2] "Notes on some Geological Features of the North-Eastern Coast of Labrador," "Canadian Naturalist," New Series, vol. viii. p. 236.

the Labrador coast, the mass will resemble boulder clay, and in a sinking marine area it will accumulate to a great thickness. In a rising area it would be liable to be remodelled by the action of the waves, except in the case of very deep valleys."

With regard to the transporting powers of the ice in the same region, Sir Charles Lyell states, on the authority of Captain Bayfield, that the coast of Labrador between the latitudes 50° and 60° N., for a distance of 700 miles, is strewed over with ice-borne boulders. Some of the blocks were six feet in diameter, and all of them, both small and large, were being conveyed in the direction of the prevailing current, viz., from north to south. Countless blocks were usually to be seen lying between high and low-water mark, but sometimes tracts of the coast were observed to be bare of boulders, and then again at another season thickly strewed with these erratics.

In parts of the Baltic stones are frequently frozen into the ice along the shores; and, when summer comes, they are lifted up, and floated away on the ice-rafts. Dr. Forchhammer relates a remarkable fact which demonstrates how large a number of rock-fragments are annually transported by ice in the Baltic. A diver went down to examine a vessel, which had sunk near Copenhagen thirty-seven years before. He found the deck covered with blocks, from 6 to 8 cubic feet in size, and some of them piled one upon the other. He also affirmed that all other sunken ships in the Sound were covered with similar blocks.

Finally, if we consider the extensive areas in the northern hemisphere, over which coast-ice is now acting, and if we regard all the deeply indented coast-lines of Scandinavia, Finland, Greenland, and North America, every yard of which is more or less subject to this action, we shall conclude, with Professor Milne, that the coast-ice must, in quantity, be much greater than that of the glaciers, and much more effective in the transport of rock débris. "All the vast ice-fields which break loose from the frozen regions of the North—and we read of them as 300,000 square miles in extent, and 7 feet in thickness—are in their passage south driven in upon the land, and help to grind the coast-

line, and transport its boulders. The northern field-ice, when it arrives in the latitudes of Newfoundland, is often seen to be covered with boulders, gravel, kelp, and other materials, showing it to have been, at some time or other, in contact with the coast."[1] The distance to which these materials may be transported is indicated by the southward extension of icebergs in the Atlantic.

[1] "Geol. Mag.," Dec. 2, vol. iii. p. 408.

CHAPTER XV.

MARINE DEPOSITS (*continued*).

Shallow-Water Calcareous Deposits.

IN this chapter we shall consider all the calcareous deposits which are being formed in water of less than 300 fathoms in various parts of the world, whether they are due to direct chemical precipitation, or to the accumulation of dead shells, corals, and other organic débris. Both kinds of deposit are really due to the abstraction of lime from the sea-water by chemical processes, for the carbonate of lime which constitutes such organic structures has been obtained by the action of organic secretions on the salts dissolved in the sea.

I. *Deposits formed by Chemical Precipitation.*

It used to be supposed that the free carbonic acid in sea-water was more than sufficient to keep in solution all the carbonate of lime usually found in it. More recently, however, Herr Tornoe, of the Norwegian North Atlantic Expedition, asserted that there was no free carbonic acid at all in sea-water, and that the amounts reported as existing were really combined with lime in the form of carbonate; he appealed also to the fact that sea-water has generally an alkaline, not an acid, reaction. It seems to be now admitted that there is more carbonate of lime dissolved in sea-water than was formerly supposed, but still the quantity is very small (see Analysis, p. 246); and there is also some free carbonic acid. Dr. Buchanan's observations on board the "Challenger" show that the free carbonic acid present is subject to great variations, being greater near the bottom

than in surface-water, and also greater in those waters where animal life is most abundant.

The quantity of dissolved carbonate of lime also varies, but recent inquiries point to the conclusion that sea-water is a compound which refuses to hold much carbonate of lime in solution. Dr. J. Murray has made experiments to ascertain how much it can take up, and finds that 0·6490 grammes per litre (about five times the ordinary amount in solution) can be dissolved, forming a clear super-saturated solution, but after a time not only the excess so added is thrown down, but also sometimes a portion of that normally present in the water.[1] What, therefore, becomes of all the carbonate of lime which is being annually carried into the sea by rivers? it used to be thought that it was taken up and used by marine creatures, but it seems more probable that it is disposed of either by precipitation or by immediate conversion into sulphate of lime.

Mr. J. G. Goodchild has suggested that most of the carbonate of lime carried down by rivers is converted into sulphate of lime. He refers to a statement by Dr. Sterry Hunt, that if a solution of carbonate of lime in carbonated water be mixed with a solution of sulphate of magnesia in water, double decomposition ensues, and carbonate of magnesia and sulphate of lime are formed. The difficulty in supposing this reaction to occur lies in accounting for the carbonate of magnesia that would be formed, for none exists in sea-water.

It appears to be a fact that where much carbonate of lime is brought down by rivers, some of this material is precipitated and forms a calcareous deposit. Thus a hard calcareous rock is being formed on the sea-bottom opposite the mouths of the Rhone in the Mediterranean, and along the coast of Languedoc.

Lyell states that large masses of hard rock, consisting of sand cemented by calcareous matter, are continually found, and that a cannon, embedded in crystalline, calcareous rock, taken up from the sea near the river's mouth, may be seen in the museum of Montpelier.[2]

Deposits of the same kind are found along the southern

[1] "Proc. Roy. Soc. Edin.," and "Nature," June 12, 1890, p. 165.
[2] "Principles of Geology," tenth edition, vol. i. p. 430.

coast of Asia Minor. Admiral Sir F. Beaufort found that great alterations had taken place on this coast since the time of Strabo: havens have been filled up, islands are joined to the main land, and many miles of new land have been formed, consisting of compact stone. Almost all the rivers and streams contain abundance of carbonate of lime in solution, and the precipitation of this binds together the sand and gravel in the river deltas, and converts them into calciferous sandstones and conglomerates.[1]

In accounting for this deposition of limestone, Lyell observes "that the fresh water introduced by rivers being lighter than the water of the sea, floats over the latter, and remains upon the surface for a considerable distance. Consequently, it is exposed to as much evaporation as the waters of a lake; and the area over which the river-water is spread, at the junction of great rivers and the sea, may well be compared, in point of extent, to that of considerable lakes."

It is probable, also, that a chemical action goes on where the under surface of this body of fresh water is in contact with the salt water. Dr. Murray's experiments above mentioned suggest that such action does take place, and the precipitation of the carbonate of lime may be due either to the presence of alkaline salts or to the abstraction of part of the carbonic acid which kept it in solution. The formation of solid limestones in shallow waters by one or both of these processes is, at any rate, an ascertained fact, so that the view taken by some writers, that all marine limestones have had an organic origin, does not seem to be correct.

The chemical precipitates formed from sea-water by evaporation and concentration when land-locked lagoons have been separated from the sea have been described under the head of lacustrine deposits (see p. 246).

Chemical Reactions of Marine Organisms.—The capacity of marine creatures to form calcareous shells and skeletons involves questions of much interest to geologists. It used to be supposed that they had the power of simply abstracting the carbonate of lime, and that the quantity of that mineral found in sea-water was small because most

[1] *Op. cit.*, p. 431.

of it had been so abstracted; but if this were so, we should expect to find that the amount of carbonate of lime in solution was still very large near the mouths of rivers, and that it became less and less toward the open ocean. This, however, is not the case; on the contrary, the composition of sea-water in narrow seas and estuaries is practically the same as that of water far from land, and yet the amount of animal life in estuaries is generally less than in the open sea. Moreover, as we have seen, there are other ways of accounting for this sudden disappearance of the carbonate of lime.

How then do marine creatures get the carbonate of lime for their calcareous structures? Recent researches seem to prove that they have the power of getting it from the sulphate. Experiments [1] by Messrs. Irvine and Woodhead have shown that animals with a circulatory system can take up any salts of lime in solution and convert them, first into phosphates, and finally into carbonates. More recently Murray and Irvine, experimenting with the liquor of oysters and mussels, found that it contained a great excess of carbonate of lime over that in sea-water, and they refer this to the direct secretion of carbonate of ammonia by the cells of the living animals, which, reacting on the sulphate of lime in the sea-water, is capable of throwing out nine-tenths of the calcium salt in the condition of carbonate.[2] They believe that many marine animals secrete carbonate of ammonia as an effete product, and referring to corals, they say: "In polypes, which, unlike the higher animals, have no true circulatory system, and where the animal is immersed in sea-water, it seems hardly possible to account for the enormous secretion of carbonate of lime in the manner indicated by Bischoff; but if the conclusion we have arrived at be correct, and such animals, in place of secreting urea, secrete carbonate of ammonia, then we have a perfectly reasonable explanation of the phenomenon of coral formation."

It may be added that by this process we are also able to understand why the sea-water in the neighbourhood of coral-reefs is sometimes so saturated with carbonate of

[1] "Proc. Roy. Soc. Edin.," 1888-9, part xvi.

[2] "Proc. Roy. Soc. Edin.," and "Nature," June 12, 1890.

lime that the retiring tide leaves a thin white coating of it on the pebbles of the beach. Dana describes a beach on Oahu, one of the Sandwich Islands, where "the pebbles are covered with a thin incrustation of carbonate of lime, appearing as if they had been dipped in milk, while others are actually cemented (together), yet so weakly that the fingers easily break them apart." On the island of Ascension the rocks situated at the end of a long beach of calcareous sand are regularly coated every year with a white, thick, and hard deposit of carbonate of lime.

Calcareous Mud and Limestone Paste.—As we shall presently see, the fragments of the calcareous shells, tests, and skeletons of various kinds of sea creatures, make up a large part of most marine limestones, sometimes as much as 90 per cent.; but besides these definite organic fragments, there is always a certain amount of fine calcareous sediment which fills up the spaces between the fragments: and there are some limestones which consist entirely of such a calcareous paste, with very few recognizable organic fragments in it.

To account for this paste several explanations have been suggested: (1) When the chitinous membrane which holds together a calcareous shell has decayed, the carbonate of lime is attacked by carbonic acid, and is so loosened by partial solution that it falls to pieces, and is gradually reduced to a fine kind of powder. (2) Another source of fine sediment is to be found in the trituration of calcareous sand in the intestines of sea creatures; this is an active process in some localities, especially on coral reefs, where holothurians, or sea-cucumbers, are very abundant; these creatures swallow the sand, and obtain nutriment from the diatoms, foraminifera, and other minute organisms which occur in it, the hard calcareous particles being voided. But everywhere all kinds of echinoderms, molluscs, crustacea, and fish are actively engaged in a similar process, and must expel large quantities of triturated calcareous material. Dr. Guppy states that fifteen or sixteen holothuria are capable of discharging a ton of such material in the course of a year. This production of calcareous mud is also assisted by the detritive effect of waves on such portions of calcareous rock as come within their action. (3) There is still

another way in which calcareous mud may be produced, and that is the action already mentioned of carbonate of ammonia on sulphate of lime. Messrs. Murray and Irvine state that if animals such as crabs are allowed to die in a limited amount of sea-water, the carbonate of ammonia formed, with other products of decomposition, precipitates all the calcium sulphate in the water as carbonate. Thus not only do marine creatures secrete carbonate of lime while they are alive, but their decay after death also cause a precipitate of the same substance; and Mr. Goodchild aptly remarks, that "such action is not by any means necessarily limited to the tenants of the sea-floor, for the decomposition of pelagic organisms is likely to contribute more or less to the same result. Nor is it limited to organisms with calcareous frameworks, but may result just as much from the decay of, say, jelly fishes or sponges, as from their lime-secreting allies." [1]

On these grounds we may safely agree with Mr. Goodchild in concluding that "chemical precipitates due to the action of decomposing organic matter upon sulphate of lime have an essential influence upon the formation of limestones, even when these are mainly of organic origin"; and that if these views are correct, we must regard "all limestones as of compound origin, partly organic, partly detrital, and partly as chemical precipitates, the proportion of each to the others varying to a much greater extent than has yet been recognized."

II. *Deposits formed of Organic Débris.*

We will now consider the formation and distribution of calcareous deposits, which consist largely of organic débris.

1. **Shell Sands.**—The materials for the construction of calcareous sandstones, or sandy limestones, are being accumulated round many coasts, and are common in the English Channel and off the west coasts of France and Britain.[2]

In the western part of the Channel deposits of broken shells and shell-sand form three long, occasionally inter-

[1] "Geol. Mag.," Dec. 3, 1890, vol. vii. p. 78.
[2] See "Lithologie du Fond des Mers," par Delesse, Paris, 1872.

rupted, bands which unite at the mouth of the Channel between Cornwall and Brittany to form a large spread of shell-sand. There are also extensive tracts of shell-sand along the north coast of France, especially along the sweep of the coast from Calais to Etretat, on each side of the Cotentin, and in the Bay of St. Brienc. The littoral portions of these deposits are dug for marling the land.

There is also a large tract of calcareous shelly sand off the west coast of Brittany, extending seawards for over 60 miles, nearly down to the line of 200 fathoms, where its front is over 100 miles long.

In the Irish Sea there are frequent records on the Admiralty charts of shells, or sand with shells, especially in the central area between Wales and Ireland; there is a tract of irregular shape and varying width extending from the coast of Anglesey to the deep water east of Wexford, a distance of 100 miles, where shells and shell-sand largely prevail, mixed with some quartz-sand, and occasionally fine sand or mud.

On our north and north-west coasts beds of shells occur round the Hebrides and over a bank to the south-west of the Faroe Islands. Still further west, around the isolated reef in the Atlantic known as Rockall, there are beds of shell débris, and also a deposit formed entirely of fish remains, and extending for a distance of three miles.

2. **Limestone Banks.**—Immense accumulations of organic débris are being formed on the sea-floor in some tropical regions; one of the best known is that called the Pourtales plateau, south of Florida. Outside the Florida reefs, down to about 90 fathoms, the bottom consists of calcareous mud, but beyond that is a wide plateau sloping gently to 250 or 300 fathoms, and 18 miles wide at its western end. This wide shelf or plateau has a rough rocky floor, consisting of the remains of various organisms, deep-water corals, shells, echinoderms, polyzoa, crustacea, etc., mixed with shell-sand, and frequently cemented together by carbonate of lime, so that large slabs of solid limestone were dredged up from it.

Professor A. Agassiz has shown that raised banks of similar limestone form the foundation on which the coral-reefs of Florida have been built up; and he describes

other great plateaux or banks in the same seas which consist of the same materials, especially off the coasts of Yucatan and Honduras. A large part of Yucatan consists of precisely similar limestone which has been raised into dry land, and is now traversed by caverns and fissures, some of which have been explored to a depth of 400 feet; this shows how great a thickness of such material may be built up by the accumulation of organic débris in seas like these which are literally teeming with life.

3. **Coral-reefs.**—Coral-making Actinozoa exist in all temperate and tropical seas, and are found at various depths. The great *reef-making* corals, however, cannot exist in waters where the temperature ever falls below 68° F.; they are, therefore, confined to those parts of intertropical seas which are never invaded by currents of water colder than 68° F. Moreover, these coral-polyps can only live in shallow water, and are generally found within a depth of 25 fathoms, though some species under favourable circumstances appear able to grow in 30, or even 40 fathoms. Another condition necessary for the growth of coral-reefs is clear water. Mud is always detrimental to animal life, and the coral-polyp is especially sensitive to the influx of muddy water brought down from the land.

Even within the tropics the growth of coral-reefs may be prevented by any of the following causes:—

1. The too great depth of the water.
2. The occasional influx of cold water.
3. The frequent influx of muddy water.
4. The impingement of too strong a current.

Coral-reefs are generally divided into three kinds or classes,—Fringing-reefs, Barrier-reefs, and Atolls.

Fringing-reefs are those which are formed along the margin of any coast or island. If the slope of the shore below water is steep, the reef is a narrow one; if the slope is gentle, a wider fringe of reef will be formed, its outward extension being dependent upon the depth of the water. It must not be supposed that a fringing-reef always forms a level platform which is wholly dry at low water; such shore-reefs do occur in some places, but the exposed part of a fringing-reef is generally from half a mile to a mile from the beach, and sometimes more than a mile. The in-

termediate space is covered by water, sometimes only 3 or 4 feet in depth, and sometimes 3 or 4 fathoms, so as to afford a passage for boats. Its floor is generally coral-sand, with here and there tufts and bosses of living coral. This channel communicates at intervals with the sea by openings through the outer reef.

Barrier-reefs are defined by Darwin as differing from the above "in being placed at a much greater distance from the land with reference to the probable inclination of their submarine foundations, and in the presence of a deep-water lagoon-like space within them." The longest barrier-reef in the world is that of the north-east coast of Australia; this extends, with a few interruptions, for nearly 1,000 miles, its average distance from the coast being between 20 and 30 miles. The channel or arm of the sea inside it is from 10 to 20 fathoms deep, with a sandy bottom, and at its southern end, where the reef is further from the shore, it is as much as 40 to 50 fathoms deep. Mr. Jukes[1] compares it "to a great submarine wall or terrace, fronting the whole north-east coast of Australia, resting at each end on shallow water, but rising from very great depths about the centre; its upper surface forming a plateau covered by 10 to 30 fathoms of water, but studded all over with steep-sided block-like masses which rise up to low-water level. These masses are especially numerous and most linear along the edge of the great bank on which they rest, the passages between them being often very narrow, like regular embrasures opened here and there through the parapet wall of a fortress. These 'individual reefs' running along the outer edge protect the comparatively shallow water inside, and with the numerous inner reefs that are scattered over its space make it one great natural harbour."

New Caledonia, in the western Pacific, has a barrier reef off its western coast which is 400 miles long, and seldom approaches to within 8 miles of the shore.

Some islands are entirely surrounded by a reef which lies at a distance of several miles from the shore, and is separated from it by a deep-water channel; such reefs

[1] "Manual of Geology," second edition, p. 131. See also "Voyage of H.M.S. 'Fly,'" vol. i. ch. xiii.

were termed by Darwin "encircling barrier-reefs." Vanikoro, in the South Pacific, has such an encircling reef, and the inside channel is in some places 40 to 50 fathoms deep.

Some encircling reefs have only a very small island in the middle of a large lagoon-like space of water. Between such reefs and atolls there is very little difference, an atoll being a reef that encircles a lagoon without any island, except such as consist of coral.

Atolls are of all sizes, and almost all shapes, sometimes nearly circular, sometimes long and narrow, and varying from half a mile to 50 or 60 miles across. The lagoon may be shallow, but is generally deep. The reef generally supports a string of islands which are entirely composed of coral-rock, the part above the sea-level consisting of broken corals and coral-sand drifted up by the waves and winds, and subsequently consolidated into rock. The living reef outside is submerged at high water, but at low tide a broad, bare, rocky plateau is presented to view with pools and holes, which swarm with molluscs and other animals; this plateau being often intersected and broken up by winding creeks and channels.

The view of a coral-reef has been thus described by Mr. Jukes:[1]—"A coral-reef is a very different, and in itself a much less interesting and beautiful object than I had expected; neither are the colours of the living corals so splendid as is often said. The mass of the reef is a dark-brown, close, hard rock, with here a patch of white sand, and there a lump or a mass of living corals, some of the smaller of which are grass-green, yellow, or red. When sailing among the islands, however, the reef and the islands often formed most beautiful objects, as seen from the poops, or mizen-top. The little island, crowned with trees, is surrounded by a smooth space of clear, shallow water of a bright, grass-green colour, round which is a narrow fringed margin of white foaming surf, sparkling in the sun, dividing the lagoon from the rich clear blue of the deep water outside."

The seaward or windward side of coral-reefs is always exposed to the battering and pounding action of a heavy

[1] "Letters of J. B. Jukes," Chapman and Hall, 1871, p. 173.

Fig. 67. View of a Coral Island (Atoll).

surf, since the long roll of the ocean-swell falls suddenly upon the upper edge of the reef and dashes over its surface in huge breakers, that are sometimes felt even all across it. If a mass of coral, living or dead, be once detached from the rest, it is soon acted upon by these breakers, and ultimately triturated into calcareous sand.

The large solid corals, such as Porites, Astræa, and Mæandrina, grow chiefly along the outer margin of the reef where the breakers are continually rolling over them. The more delicate and branching forms, like Explanaria and Madrepora, flourish in the central lagoon, or in the more sheltered channels between the outer reefs. The top of the reef is often encrusted and heightened by a growth of calcareous seaweed called Nullipora, which sometimes forms a stony coating two or three feet in thickness, and resists the force of the waves.

Construction of Coral-rock.—Jukes describes the composition of the solid reef-rock in the following terms:[1]—

"Coral-reefs consist of living corals only in parts of their upper surface, and along their outside rim, which is a mere film compared with their whole bulk. All the interior is composed of dead corals and shells, either whole or in fragments, and the calcareous portions of other marine animals. The interstices of the mass are filled up and compacted together by calcareous sand and mud, derived from the waste and débris of the corals and shells and of countless myriads of minute organisms, mostly calcareous also. The living part, even of the upper surface of the reef, is that only which is never dry at low water. The part which is then exposed is composed of mere stone, which is often capable of being split up and lifted in slabs, bearing no small resemblance to some of our oldest limestones. These slabs and blocks, when broken open, are frequently found to have a crystalline structure internally, by which the forms and the organic structure of the corals and shells are more or less disguised and obliterated. A coral-reef, then, of which a part is still living and in process of formation above, may internally consist of solid crystalline limestone."

[1] "Manual of Geology," third edition, p. 388.

Upon this compact basis the wind often raises banks of calcareous sand derived from the waste of corals and shells, and these are compacted into masses which are very different from the lower portion of the reef. "The large fragments of corals and shells are never found much beyond the surf range of high-tide, and therefore always form rock at a low level; whilst, on the contrary, the fine calcareous sand is removed by the wind and deposited in irregularly laminated beds, which being consolidated in various degrees, are converted into rock of different qualities." [1] This consolidation is effected by the action of percolating rain-water, which dissolves some of the carbonate of lime from the surface layers and re-deposits it below in the form of a calcareous cement, so that the loose grains of sand are thus bound together into a solid mass. Captain Nelson describes the ordinary coral rock of Bahama as forming a strong and homogeneous calcareous sandstone, soft and loose near the surface, but harder below, and capable of being used for building purposes. "It is somewhat similar to Portland stone in appearance, but softer and more porous. When first exposed it is quite white, but becomes of a dark ashen-grey colour along the sea-coast, and elsewhere when exposed to the weather. On some reefs the rock formed in this manner is distinctly *oolitic*, each particle being enveloped in two or three concentric coats, like the coats of an onion."

Among coral-rocks the following varieties may be distinguished:—

1. A rock consisting of corals standing as they grew, the interstices being filled with broken fragments, shells, and coral-sand.

2. A breccia of large blocks of coral and previously formed coral-rock embedded in sand, and often cemented together by carbonate of lime.

3. A rubbly rock consisting of broken pieces of coral, with shells and other organic débris.

4. A fine-grained rock consisting of small fragments of corals, shells, echinoderms and nullipores, with foraminifera, which are sometimes very abundant.

[1] Nelson on the Bahamas, "Quart. Journ. Geol. Soc.," vol. ix. p. 206.

5. Fine-grained compact limestones formed by the cementation of the rocks grouped under No. 4.

6. Oolites formed of round concretionary grains.

The first three are reef-rocks, the last three are lagoon and beach-rocks.

Coral Mud.—Fine calcareous mud is also formed by the further trituration of the dead corals and coral-sand, and is often accumulated in the quiet waters of the internal lagoons and channels. Such is the case in some of the inner channels and lagoons of the Bahama Islands, especially along the western coast of Andros Island, which is bordered by an extensive deposit of fine, chalky mud, thus described by Captain Nelson:[1]—"The western shore of the island is generally a stiff chalk-bank, four or five feet high, sloping inwards to the marshy chalk-flat which surrounds the fresh-water lake of Andros Island; at its eastern limit it abuts against a narrow ridge of hills along the centre of the islands. Parallel to the western coast and seaward, with a breadth of 14 or 15 miles, the chalk continues in mass as an anchorage," and beyond this it is spread out as a thin covering over the sandy bottom for a space of about 80 miles in length by about 60 in extreme width, the area being rudely heart-shaped.

Where slopes are steep, as they are near barrier-reefs and atolls, some of the mud so formed is carried out by the tides into the deeper water outside the reefs, and is spread over the bottom below the 50-fathom line, where it forms a thick deposit of fine calcareous mud, or ooze. Mr. Jukes states that wherever deep soundings were taken round the north coast of Australia, the "bottom" was found to consist of a very fine, almost impalpable, pale olive-green mud, which was entirely soluble in hydrochloric acid, and therefore consisted of carbonate of lime. The greater part of this material is probably obtained from the washings of the coral reefs, though a certain proportion may be derived from the shells of oceanic mollusca.

The soundings obtained by the "Challenger" expedition near the Bermudas, from various depths within a certain

[1] "Quart. Journ. Geol. Soc.," vol. ix. p. 208.

distance of the reefs, showed that in all cases the bottom consisted of "soft, white, calcareous mud, evidently produced by the disintegration of the Bermuda reef and of the multitude of Pteropod shells which sink down from the surface."[1]

In the contracting lagoons of certain coral islands, it appears possible for a compound of the carbonates of lime and magnesia (called Dolomite) to be formed. Analyses of the coral limestone of Matea have demonstrated that magnesia is largely present in some specimens of the rock, one specimen affording as much as 38 per cent. Dana thinks that this limestone must have been formed in a lagoon where the soft coral mud was mixed with a deposit of magnesian salts obtained from the sea-water as the solution became gradually concentrated by evaporation.

Thickness of Reef-rock.—As reef-building corals can only live in water of a certain depth, it might be supposed that coral limestones would seldom be of any great thickness; that in a stationary area they could not be much more than 200 feet thick, that in a rising area the thickness would be less, and could only greatly exceed that amount in an area which had for a long time been slowly subsiding beneath the sea.

It must be remembered, however, that the outside of every reef is constantly exposed to the action of the waves, and that much of the dead coral is broken up into sand, which often accumulates on the slopes outside the reef, and is arranged by currents in beds and banks of coral-sand. Where the outside slopes are gentle, portions of the sea-floor are being continually built up to within 30 fathoms, and may then be occupied by coral-polypes, and be converted either into extensions of the shore-reef, or independent and isolated outer reefs. The precise mode of growth must depend partly on the conformation of the sea-floor and partly on the strength of the currents; where the sand is kept in constant motion corals will not grow, but where it is at rest they find a footing.

There is therefore no reason why several hundred feet of calcareous detritus should not be deposited outside a

[1] "Voyage of the 'Challenger,'" vol. i. p. 289.

reef, or why the reef itself should not in time extend over a large portion of it, the entire mass being eventually consolidated into a limestone, the whole of which would, if elevated, be called "coral-rock."

As a matter of fact the thickness of "coral-rock" on some raised coral-islands is known to be more than 200 feet. Thus in Barbados numerous deep wells have been made which prove the rock to be in some places 230 feet, and in one case 260 feet, but observation and inquiry showed that the lower part of the raised reefs generally consisted of débris-rock, without corals in position of growth, and varying in thickness from 5 to 60 feet.[1]

The greatest actual proved thickness of any one mass of coral-rock is in Oahu (Hawaian Islands), where a boring is said to have been carried for 900 feet through "hard ringing coral-rock into sand and lava," but how much of this contained coral-blocks is not known. Another boring was 1,500 feet deep, passing through beds of gravel, coral, clay, and lava, one mass of coral-rock being 505 feet thick, resting on 195 feet of clay and gravel, beneath which was again 28 feet of coral-rock. Such a superposition suggests subsidence, but the latest movement of the island has certainly been one of upheaval,[2] and there is no kind of barrier-reef around it.

In an area of subsidence it is obvious that a great thickness of actual reef-rock might be formed, because the corals could grow upwards as the land sank, and doubtless would do so in preference to growing outwards. Here, however, we are met by a difficulty. It is always difficult to prove subsidence (see p. 65): how then are we to know that an island of which no historical records exist has sunk, and how estimate the extent of subsidence? Deep borings are few, and have not been watched by scientific men. It has been supposed, however, that barrier-reefs and atolls are in themselves proofs of subsidence; this is Darwin's theory of the origin of such reefs, and this theory we must now state and examine.

Theories of Coral Growth.—Darwin pointed out what

[1] See "Quart. Journ. Geol. Soc.," vol. xlvii. pp. 211, 216.

[2] See Professor A. Agassiz, "Bull. Mus. Comp. Zool.," 1889, p. 152.

has been already stated, that there is the closest connection between atolls and encircling barrier-reefs, and that one might be formed on the basis of the other if the island foundation had gradually sunk. In the same way he said a fringing-reef might by subsidence be converted into a barrier-reef.

The upward growth of a coral-reef over a sinking island is illustrated in fig. 63, the horizontal lines, s^1, s^2, s^3 representing the sea-level at different periods, and indicating the amount of successive subsidences. When the sea was at the level s^1, the mass of the island was above water and the fringing-reefs, F F, were formed round its shores. Continual, but gradual, subsidence carried the land downward while the reefs have grown nearly vertically upward, until the sea-level came to coincide with the line s^2. By this

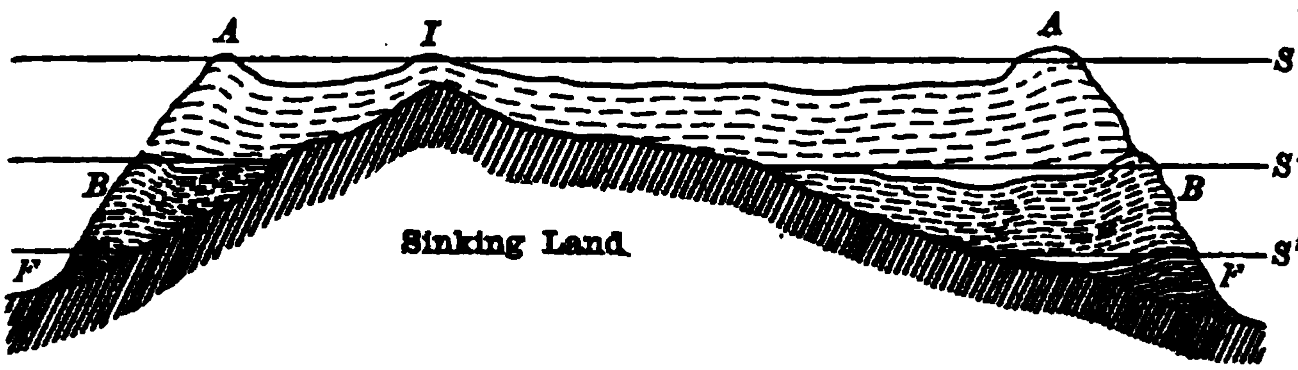

Fig. 68. Conversion of a Fringing Reef into an Atoll by Subsidence.

submergence the limits of the land would be much contracted, and the distance between its shores and the encircling reefs would be correspondingly increased, so that the latter were eventually converted into barrier-reefs, B, B. At the stage s^2, these reefs lay at a considerable distance from the coast of the sinking island, and were separated from it by a wide lagoon.

If the subsidence still continued, the width of this lagoon would still further increase, and every part of the land would be covered with a growth of coral, until the whole was converted into an atoll, A, A, or ring of reefs without a central island; except, perhaps, an inner reef raised upon the last disappearing point of land, as at I.

This theory, at once so simple and comprehensive, met with universal acceptance, and was for many years be-

lieved to be the true explanation of the origin of such reefs. It is, indeed, very probable that some reefs and atolls have been formed in this way, the mistake made by Darwin, and still more unreservedly by Dana, was in assuming that all barrier-reefs and atolls had been so formed, and that every such reef might be considered as a proof of subsidence.

More recently Professor Semper, from a study of the Pelew Islands (1863); L. Agassiz and Leconte, of the Florida Reefs (1851-66); Dr. J. Murray, from the "Challenger" Expedition (1880); A. Agassiz, writing on the Florida Reefs (1882); Dr. Guppy, on the Solomon Islands (1884-87); and Mr. J. C. Bourne, on the Coral Formations

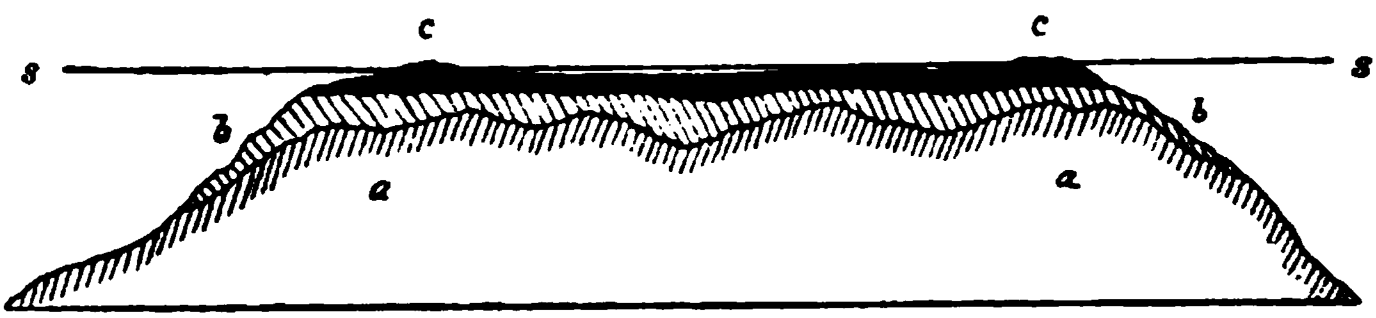

Fig. 69. Diagram to illustrate Dr. Murray's theory of the basis of Coral-reefs.

a a. The original bank. *b b*. Deposit of organic débris. *c c*. Coral. *s s*. Level of the sea.

of the Indian Ocean (1888), have all dissented from Darwin's conclusions. These writers have pointed out the following facts among others:—

1. The three kinds of reefs,—Fringes, Barriers, and Atolls,—frequently occur in the same group of islands.

2. That all these kinds also occur within regions which are known to have been recently elevated, as, for instance, the Florida region and that of the Solomon Islands.

3. That recent observations have shown how submarine banks and ridges may be built up by accretion till they form foundations for coral-reefs.

The careful examination of the reefs of Florida and the adjacent islands, by Professor A. Agassiz, leaves little doubt that they are based upon the great shell-banks which exist in those seas, and which are still being formed (see p. 279).

Fig. 69 shows how a submarine bank, ridge, or eminence may be heightened by the gradual accumulation of organic débris till its surface is brought within the depth of water in which reef-corals can live, and how an atoll-like reef may then be built upon it.

Ocean shoals are much more numerous than was suspected in Darwin's time, and every submarine eminence is being heightened by the accumulation of organic débris on its surface. Mr. Murray has estimated that in tropical

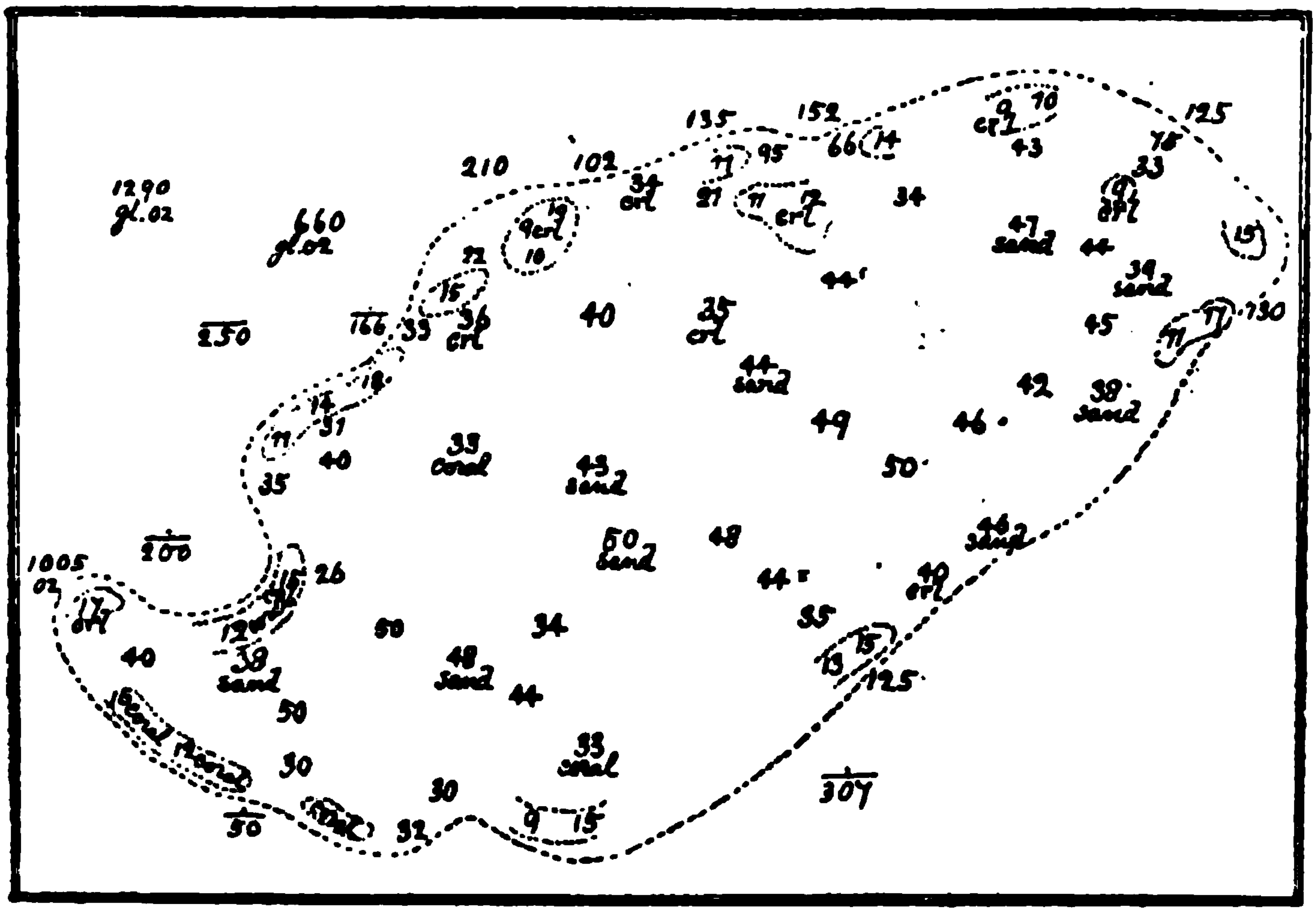

Fig. 70. Chart of Macclesfield Bank (after Capt. Wharton). Scale 20 sea-miles to an inch. Soundings in fathoms.

seas a square mile by 100 fathoms deep contains over sixteen tons of carbonate of lime in the shape of living organisms; and besides this there are all the creatures which grow or creep on the surface of the shoal itself.

Again, in volcanic regions cinder-cones often form temporary islands, which are gradually worn down by the waves till only a submarine shoal remains, and this would form a suitable foundation for a coral island.

Finally, Captain Wharton has called attention to certain

submarine banks which present the appearance of being atolls in the process of formation.[1] Thus the Macclesfield Bank in the China Sea is a large oval area 70 miles in length, the central part of which is covered by 40 or 50 fathoms of water, but all round its rim are a series of growing coral-reefs, some of which rise to within 10 fathoms of the surface (see fig. 70). The Tizard Bank in the same sea presents similar features, but in this case some of the reefs have actually reached the surface, while others are still 4 or 5 fathoms deep.

Dr. Coppinger, describing the Admirante Islands in the Indian Ocean,[2] says they stand on an oval-shaped bank which has a raised rim and a central depressed area, and he remarks that several of the islands present positive evidence of elevation. The African Islands exhibit similar features. Here, therefore, we have banks with the aspect of submerged or imperfect atolls which bear direct evidence of upheaval, not subsidence.

The Tonga Islands in the Pacific afford instances of raised coral-limestones resting on stratified volcanic ash and tuff. Falcon Island, which is one of the group, and was described on p. 45, shows how this basis may be prepared; and Mr. J. J. Lister has shown that elevation has been in progress for a great length of time, raising coral-reefs on Eua and Vavau to heights of 500 and 1,000 feet above the sea.[3]

Given a foundation, we only need an explanation of the special coral growth on its border to understand the formation of an atoll. This is not difficult. All writers (Darwin included) agree that the corals which establish themselves on the outer parts of a shoal are likely to grow more vigorously than those on the inner parts, because they get a more abundant supply of food in the sweep of the ocean currents. The currents themselves too exert a directing influence: several observers, notably Semper, Bourne, and Hickson, lay stress on this influence, and state that corals will not flourish in a very strong current (6 or 7 miles an hour), nor in still water, but grow

[1] "Nature," Feb. 23, 1888, p. 393.
[2] "Cruise of the 'Alert,'" p. 225.
[3] "Quart. Journ. Geol. Soc.," vol. xlvii. p. 590.

luxuriantly in places where a moderate current flows over them. Such conditions exist on the outer slopes of a submarine bank more than over its central part.

Moreover, when once the outer reefs have grown up so far as to come within the influence of wave action, other causes come into play; broken fragments and dead coral-blocks are piled on these reefs, while fine sand and sediment are carried inward over the lagoon area, and are kept in movement by every tide. This exerts a great repressive influence on the coral growths of the central space; and this repression is aided by the boring and excavating action of certain worms, Molluscs and Echini, which attack dead coral, and possibly also (as Murray suggests) by the actual solution of some of the dead coral. Sediment in motion, however, seems to be the chief check to coral growth, and where the scour of the tide is not very great the lagoon is sometimes being choked up with sediment, as in the Cocos-Keeling Atoll.

Putting all the preceding considerations together, we arrive at the conclusion that Darwin's theory cannot be accepted as a general explanation of Atolls and Barrier-reefs, and that the inferences drawn from it as to the great thickness of coral-rock beneath some reefs cannot be entertained without further evidence.

Both Professor Agassiz and Dr. Guppy truly remark that Darwin and Dana were not justified in assuming the submarine slope outside a coast-line to be a prolongation of the exposed land-slope. Such a mode of reasoning is very fallacious, and cannot lead to accurate results. Experience has shown that submarine slopes are very irregular, and are often broken into a series of gentle inclines with short, steep slopes between them. It has also been found that there are such things as submarine barrier-reefs as well as submarine atolls, that is to say, wall-like reefs which rise from ledges where the corals are forced to grow upward, being limited on the one side by deep water and on the other by unstable sand or mud derived from a reef nearer the shore which is exposed to wave-erosion.[1]

[1] See Guppy, "Proc. Roy. Soc. Edin.," 1886, p. 880; Jukes-Browne and Harrison, "Quart. Journ. Geol. Soc.," vol. xlvii. p. 204; and Captain Wharton, "Nature," 1888, p. 395.

CHAPTER XVI.

DEEP-SEA AND OCEANIC DEPOSITS.

WE have now to consider the deposits which are being formed in the great oceanic depressions which lie outside the shelf or zone of comparatively shallow water which border the continental areas. These deposits may be classified as follows:—

1. Blue muds.
2. Glauconitic marls and sands.
3. Calcareous oozes.
4. Red clays.
5. Siliceous oozes.

1. *Blue Muds.*—It was mentioned on p. 267 that the finest part of the sediment derived from the waste of land-surfaces is carried for a certain distance into the seas and oceans. This sediment forms a layer of blue mud, and there is generally a band of such mud immediately outside the sands which border the coasts of the great continents. It often extends to considerable depths, but seldom covers a large area except where great rivers discharge into wide bays or gulfs. Thus in the Arabian Sea and in the Bay of Bengal blue mud extends to a distance of 700 miles from land and down to depths of more than 2,000 fathoms, and covers an area of about 1,700,000 square miles.[1] Dr. Murray describes these muds as soft and reddish at the surface, but stiff, blue, and tenacious underneath. They contain much more organic matter than the more remote oceanic deposits, and it is the slow decomposition of this which, by reducing the higher oxides, gives the mass a

[1] See map and description of the deposits in the Indian Ocean, by Dr. J. Murray, in the "Scottish Geographical Magazine," August, 1889.

bluish tint. The mineral particles which make up the bulk of the deposit are of various kinds, and quartz grains are generally present.

Along the east coast of South America there is a deposit of analogous origin and composition, but it is red instead of blue, deriving its colour from the presence of peroxide of iron.

Green Marls and Sands.—These occur chiefly along high and bold coasts where no great rivers enter the sea, and where consequently deposits accumulate much more slowly than in the regions where blue mud occurs. The material of the green deposits seems to be partly terrigenous and partly pelagic, but the mineral particles appear to have been long exposed to the action of the sea-water, and to have undergone much alteration. Much of the green matter in the marls seems to be of organic origin, for when heated on platinum foil it burns, leaving a residue of carbon and red oxide of iron, but there are also grains of a green mineral known as *glauconite*, which is a silicate of alumina and iron. Shells of Foraminifera and Oceanic Mollusca are abundant, and often form over 60 per cent. of the mass. A great number of these shells are filled with glauconite, either dark green, pale green, or yellow in colour, and where the finer sediment is washed out by a current the remainder forms a green sand. Such green sand occurs on the Agulhas Bank south of Africa, and below the Gulf Stream between Florida and Cape Hatteras, in depths of from 100 to 1,000 fathoms. Glauconite concretions containing phosphate of lime also occur at both places.

Volcanic islands are always bordered by deposits of sandy marl or mud, consisting of mineral particles derived from volcanic rocks, with varying proportions of Foraminifera and Oceanic Mollusca, but seldom, if ever, any glauconite. The coral muds which similarly surround coral islands have already been described.

Pteropod Ooze.—The surface waters of the warmer regions of the great oceans swarm with small Molluscs belonging to the classes Pteropoda, Heteropoda, and the young fry of Gasteropoda. All these have exceedingly thin and delicate shells, and, like all the minuter forms of animal life, they make up for their individual insignificance by their immense abundance, so that they actually supply

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The deep-sea soundings carried out across the North Atlantic by Captain Dayman (1857), and more recently by the officers of the "Challenger" expedition (1873-6), have made us well acquainted with the bed of that ocean. At a distance of about 200 miles from the west coast of Ireland the bed of the Atlantic slopes down rapidly to a depth of 1,700 fathoms, and thence there is a great undulating submarine plain which extends to within 500 miles of Newfoundland, when the bottom slopes gradually up again till it rises into dry land. This great plain has been called the telegraphic plateau; from east to west it measures about 1,300 miles, and from Greenland on the north to the Azores on the south its extent is about the same, most of this space being about 2,000 fathoms deep, and no part of it being deeper than 2,700 fathoms, or 16,200 feet.

Specimens of the mud at the bottom were brought up by the sounding machines during the various surveys, and that which is found all over the central space between Ireland and Newfoundland, and also far to the southward, is a kind of soft sticky or mealy substance, which was described by Captain Dayman under the name of *ooze*. This ooze is of a whitish, or greyish-white tint, and when dry resembles very fine chalk. When examined under the microscope it is found to consist chiefly of the shells of Foraminifera, and as more than three-fourths of these belong to the one genus *Globigerina*, it has therefore been termed the *Globigerina ooze*. When treated with a dilute acid, a violent effervescence takes place, and the greater part of its bulk disappears, being chiefly carbonate of lime. The insoluble remainder, usually about one-tenth by weight of the whole mass, consists partly of siliceous matter of organic origin, and partly of minute particles of pumice, felspar, augite, and other minerals which occur in volcanic rocks. The transport of volcanic dust to great distances by the winds, and of pumice by marine currents, readily accounts for the occurrence of these mineral fragments.

The analyses of calcareous oozes vary considerably, but the following is the composition of three samples:[1] two are Globigerina oozes from the North Atlantic, No. 1 from the

[1] "Voyage of the 'Challenger,'" vol. ii. pp. 374, 380.

depth of 1,900 fathoms, and the second from a depth of 1,420 fathoms; the third is a Pteropod ooze from 450 fathoms off Sombrero Island in the West Indies :—

	No. 1.	No. 2.	No. 3.
Loss on ignition . . .	6·63	3·80	4·00
Alumina and ferric oxide	5·86	4·42	4·80
Calcium sulphate . . .	0·51	2·82	1·00
Calcium carbonate . . .	74·50	80·69	84·27
Magnesium carbonate . .	1·27	0·68	1·28
Soluble silica	5·80	4·14	2·60
Residue, chiefly silicates .	5·63	3·45	2·05
	100·00	100·00	100·00

It was for some time a question whether these Globigerinæ lived at the bottom of the ocean where their shells are now found, or whether they lived in the surface waters, their shells only falling to the bottom when the animals died. The observations of Dr. Murray, during the voyage of the "Challenger," proved the latter to be the truth. He found that the Globigerinæ swarmed at and near the surface in such numbers that their shells must fall like an incessant rain through the waters of the ocean, and must be continually adding to the deposit at the bottom. Professor Huxley has calculated that if we assume this foraminiferal shower will form in one year a layer of solid matter one-tenth of an inch thick, "then if the present state of the Atlantic Ocean has existed for only 100,000 years, this apparently unimportant operation will have sufficed to cover its floor with the materials of a bed of limestone no less than 800 feet thick."[1] Looking only to the shallower parts of the Atlantic, where the deposits bear a greater resemblance to chalk than those of the deeper waters, we see that if these were gradually uplifted above its surface, the land so produced would consist of a

[1] "Physiography," p. 267.

chalky material similar to that which occupies so large a portion of the continent of Europe.

The Globigerina ooze of the North Atlantic has been specially described because the first explorations were made in that ocean, but it is also the prevalent deposit in the South Atlantic, Pacific, and Indian Oceans, wherever the depth does not exceed 2,400 fathoms. In depths of less than 2,000 fathoms the ooze contains from 50 to 86 per cent. of carbonate of lime; but below this depth the amount rapidly decreases, the shells in it having a more and more rotten and decayed appearance; at the same time the ooze assumes a grey, and finally a reddish or brownish tint, and passes either into a red clay or a Radiolarian ooze (to be described hereafter). It would appear, therefore, that the falling shells suffer from the dissolving action of the carbonic acid in the sea-water, and that where they have to fall through more than three miles of water they lose a large portion of their substance, and are finally altogether dissolved. It would also seem that this dissolution proceeds more rapidly at great depths, probably because of the great pressure at such depths.

Red Clay.—The central part of the Atlantic Ocean is divided into two great basins by a sub-oceanic ridge, now known as the Dolphin Bank. The Azores are situate on this ridge, which slopes on each side down to depths of over 2,500 fathoms, and in two places to over 3,000 fathoms. The South Atlantic is similarly divided by the Challenger Bank, and has similar depths. The Pacific has large areas which are over 3,000 fathoms, and one part which is over 4,000. The central part of the Indian Ocean is between 2,000 and 3,000 fathoms, only three small areas being over the latter depth.

It has been stated that at depths of about 2,400 fathoms the ooze assumes a reddish tint; this is due to the higher oxides of iron and manganese, and where siliceous organisms are few, the Globigerina ooze passes into a red or reddish-brown clay, which, in the greater depths, contains merely a trace of carbonate of lime. The passage from ooze to red clay is often gradual, so that some samples which are classed as red clay contain many Foraminifera and yield from 20 to 30 per cent. of carbonate of lime.

In greater depths, however, the bulk of the deposit (over 80 per cent.) consists of fine amorphous clayey matter mixed with very minute mineral particles; in this are scattered a few larger particles of volcanic minerals, and often a large quantity of disintegrated fragments of pumice. Peroxide of manganese is also abundant, both in the form of small grains and of large nodules or concretions.

Dr. J. Murray's view of the origin of this remarkable deposit is now generally accepted; he points out that the materials of which it is formed are present in the Globigerina ooze, but are there masked by the large amount of calcareous material; if, however, this material is removed, the residue is similar in composition to the red clay, only differing in having a larger proportion of definite mineral fragments. He naturally infers that the red clay and the ooze residue have the same origin, and that they are entirely derived from the fine dust which is carried by the winds, and from the pumice which floats on the surface of the ocean. Both the pumice and much of the dust are volcanic ejections (see p. 28); the universal distribution of pumice over the ocean and the ocean-floor, and on the shores of oceanic islands, was established by the experiences of the "Challenger" expedition. The dredge often brought up bushels of waterworn pieces of it, from small grains to large lumps. Besides this volcanic material, fine terrestrial dust is often borne to great distances, and may contribute to the formation of the red clay.

When the particles of dust reach the bottom many undergo slow decomposition, and ultimately furnish the fine amorphous material which forms so large a part of the deposit. If this view of its formation be true, its accumulation must be a very slow process, and of this there are several proofs. The teeth of sharks and the ear-bones of whales are much more common in the red clay areas than any where else, but as there is no reason to suppose sharks and whales are any commoner in the waters above them, it can only be that they remain unburied for a much longer time than where ooze is being formed. Again, some of the teeth dredged up belong to extinct species, a striking proof of the slowness of accumulation in these depths. Lastly, in the red clay there is a much larger proportion of par-

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be so largely composed of Radiolaria that Dr. Murray proposed for it the name of *Radiolarian Ooze*. There is, in fact, no difference between red clay and some of the Radiolarian ooze, except the presence of Radiolaria; when these make up 25 per cent. of the mass it is called Radiolarian ooze. The siliceous organisms often make up 60 or 70 per cent. of the ooze, and include Diatoms and fragments of the spicules and skeletons of siliceous sponges.

From his Pacific experiences Sir Wyville Thomson thought that this ooze belonged to still greater depths than the red clay, the latter passing down into it by an increase in the number of siliceous organisms; he says: "If the Radiolarians live at all depths in the sea, the number of their skeletons falling to the bottom at one place must increase with the increasing depth of the water, and it becomes quite intelligible that, in a bed which is being formed at the prodigious depth of five and a half nautical miles, the tests of the Radiolarians should so preponderate over the red clay as to entirely alter the character of the deposit."[1] Further exploration, however, has not quite confirmed this view; there is often a passage from red clay to Radiolarian ooze, but it is a lateral one and not dependent on any increase of depth. Moreover Globigerina ooze sometimes passes directly into Radiolarian ooze without the intervention of any red clay.

The abundance of the shells of Radiolaria on some parts of the ocean-floor, and their rarity on other parts, has not yet been fully explained, but Dr. Murray observes that they appear to be more abundant in those parts of the ocean which have a relatively low degree of salinity, and they are not abundant in the Atlantic where the salinity is generally high.

In Barbados there is an interesting series of raised oceanic deposits, consisting chiefly of fine chalky-looking white or pale buff earths. These comprise a central mass of pure Radiolarian earth, passing both upward and downward through calcareo-siliceous earth into pure foraminiferal marl or chalk. These beds are 230 feet thick, and above them are red, pink, and yellow oceanic clays.

[1] "Voyage of the 'Challenger,'" vol. i. p. 233.

Diatom Ooze.—The lacustrine forms of the microscopic plants called Diatoms have already been mentioned (p. 239). We are now concerned with those which live in salt water. They abound in all seas, from the equator to the poles, and have been found alive in ice. According to Ehrenberg, the siliceous cases of these organisms which are annually deposited in the harbour of Wismar, on the Baltic, amount to about 18,000 cubic feet, and the mud there formed is consequently very siliceous. Ehrenberg has also shown that the finest marine silts and muds, especially such as are deposited in estuaries, contain large numbers of Diatom frustules.

It is not surprising, therefore, to find that these siliceous deposits form extensive beds in some parts of the world. The town of Richmond, Virginia, U.S., is built on siliceous marls having such an organic origin; and forming strata 30 feet in thickness. In these beds the beautiful microscopic objects, *Actinocyclus* and *Coscinodiscus* are found, as well as several species of *Navicula* and *Galionella*, some of which are shown in fig. 73.

Sir John Hooker long ago mentioned their abundance in the South Polar Ocean, and described a diatomaceous ooze as occuring near the Victoria Barrier over an area measuring about 400 miles in length and 200 in breadth. This was confirmed by the "Challenger" observations, and it was found that in passing from the tropical oceans to the great Southern Ocean which surrounds the Antarctic continent a change always took place in the character of the surface fauna, the tropical species of the pelagic organisms gradually disappearing and Diatoms becoming at the same time more and more numerous. A corresponding change takes place in the deposit on the ocean-floor, the Foraminifera becoming fewer and smaller and the percentage of Diatoms increasing, till at length the deposit becomes a Diatom ooze, which is yellowish when wet but white when dry, and then resembles meal or flour. Of this material about 70 per cent. consists of Diatoms, either whole or in fragments, and there is generally 10 or 20 per cent. of calcareous shells, the remainder being clay and mineral fragments.

Rarity of Oceanic Deposits among Stratified Rocks.—Although in this chapter some account has been

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PART II.

STRUCTURAL GEOLOGY,

OR THE STRUCTURE AND RELATIVE POSITION OF ROCK-MASSES.

THE geological significance of the principal physical operations which are now taking place in or upon the earth's crust has been considered in the first part of this volume. The knowledge thus obtained will enable us to explain the nature and structure of the various rock-masses which make up that portion of the earth's crust that is open to our observation; and to understand how the rocks have been brought into the positions in which they are now found. This part of the subject includes two branches of study: (1) the mineralogical composition of rocks; (2) the arrangement of rock-masses, and their relations to one another.

When the student is in possession of these facts he is able to enter upon a third branch of geological inquiry, namely, that of Physiography, or the evolution of the physical features of the earth's surface.

CHAPTER I.

CRYSTALS AND ROCK-FORMING MINERALS.

IN the preceding pages we have assumed that the reader possesses such an acquaintance with the commoner kinds of rock as may be obtained from any elementary treatise on Geology or Mineralogy. To comprehend what has gone before it was only requisite that he should understand the difference between such common materials as clay, chalk, sandstone, limestone, granite, etc.; but before entering upon the special study of rock-masses, it is certainly necessary to have a more considerable acquaintance with the different kinds of rocks and minerals which occur in the earth's crust. The following chapters have therefore been prepared with the object of imparting to the student just so much mineralogical information as will enable him to comprehend the contents of those that succeed them.

Petrology, or the study of the mineral components of rocks, is based on the science of mineralogy. It is not necessary, however, for geological purposes that the student should make himself acquainted with all the different minerals known to the mineralogist, because those which may be considered as the *essential* constituents of rocks are comparatively few in number. It is therefore only these special rock-forming minerals which will be described in the following pages.

Again, to understand mineralogy some knowledge of chemistry is required, and if the student has not previously acquired this, it will be desirable for him to read some elementary treatise, such as Roscoe's "Primer of Chemistry" (Macmillan's Series), or "Popular Chemistry" (Whittaker's Series). Chemistry and Mineralogy being

equally outside the scope of this manual, we shall not occupy space by giving more than a brief summary of what the student can learn elsewhere.

Chemical Elements and Compounds.—Chemical analysis has discovered that there are between sixty and seventy simple or elementary substances. All mineral bodies and all organic bodies consist either of one of these elements, or of a compound of two or more of them. Except fifteen, these are all metals, and of these metallic elements many are of very rare occurrence. Of the other fifteen some are solid, as sulphur and carbon, others are always found in a gaseous state, such as oxygen, hydrogen, and nitrogen.

Of all these elementary substances not more than eighteen enter into the composition of ordinary rock-forming minerals; these are given below, together with the letters which chemists employ to denote them.

Non-Metals.		Metals.	
Oxygen	O	Aluminium	Al
Hydrogen	H	Potassium.	K
Silicon	Si	Sodium.	Na
Carbon	C	Calcium	Ca
Boron	B	Magnesium	Mg
Sulphur	S	Lithium	Li
Chlorine	Cl	Iron.	Fe
Fluorine	F	Manganese	Mn
Phosphorus	P	Titanium	Ti

There are a great many other metals, and they are capable of being grouped into classes, the members of each class having certain characters in common; thus potassium, sodium, and lithium are metals of the alkalies; calcium and two others, strontium and barium, form the alkaline earths; and magnesium is so closely allied that it might be put in the same class.

Oxygen is the most abundant element on the earth. It combines with all the other elements except fluorine, and these simple combinations, or *oxides*, are consequently the most abundant and important compounds in nature. Oxygen combined with hydrogen, in the proportion of one atom of O to two atoms of H, forms water (H_2O). With

carbon it forms two compounds, carbonic oxide (CO) and carbonic dioxide (CO_2). In combination with silicon it makes the substance silica (SiO_2), and combined with the metals aluminium, calcium, magnesium, it forms alumina (Al_2O_3), lime (CaO), and magnesia (MgO). All these substances are oxides, and when they have no special name in ordinary use, like lime for the oxide of calcium, they are spoken of simply as the oxide of iron, or oxide of manganese.

It will be observed that the proportion of oxygen varies in different oxides, and some of the elements form two or more oxides which differ in appearance and properties; thus there are three different oxides of iron—viz., FeO, the protoxide; Fe_2O_3, the peroxide; and Fe_3O_4, an intermediate oxide. In like manner carbon forms carbides, sulphur forms sulphides, and chlorine chlorides.

Certain of the oxides of *metals*, called *basic oxides*, combine with water to form compounds called *basic hydrates, e.g.* lime (calcium oxide) with water forms slaked lime (calcium hydrate); potassium oxide similarly yields potash (potassium hydrate). The basic oxides and their hydrates are collectively termed bases.

Most of the oxides of the *non-metallic* bodies, on the other hand, combine with water to form compounds, called *acid hydrates* or *acids*, analogous in their composition to basic hydrates, but differing in their chemical properties. The simple acid-forming oxides are in this relation called anhydrides, *i.e.* bodies without water. Sulphuric acid (H_2SO_4) and carbonic anhydride (CO_2) are examples of an acid hydrate and anhydride respectively.

These *acids* unite with *bases* to form compounds termed *salts*, water being at the same time produced. Salts are neither acid nor basic in character, and their formation consists in the replacement of the hydrogen of the acid by the metal of the base, the hydrogen thus set free uniting with the oxygen of the base to form water. The salts of the acids above mentioned are denoted by changing the termination "ic" of the acid into "ate," as carbonate, sulphate, silicate; thus, sulphuric acid and magnesia unite to form magnesium sulphate and water. In this case, sulphuric acid is the acid, magnesia is the base, and mag-

nesium sulphate the resulting salt. The reaction is expressed graphically thus:

$$H_2SO_4 + MgO = MgSO_4 + H_2O.$$

Binary compounds, or the unions of two elements only, are then designated by the termination *ide*, and ternary compounds or unions, of at least three elements, are designated by the termination *ate*.

Salts can also be formed by the action of acid anhydrides on basic hydrates; and it is in this way that glass and other silicates (salts of silicic acid) are produced. Thus, if silica is heated to a high temperature with potash or soda, they will unite, and form a liquid which, on being cooled, solidifies into the transparent substance known as glass.

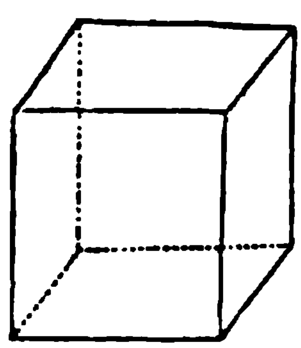

Fig. 74.

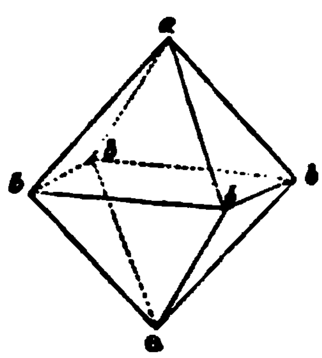

Fig. 75.

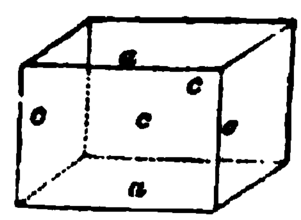

Fig. 76.

The silicates of alumina, magnesia, lime, and iron are the principal constituents of one class of rocks.

Crystallography.—A crystal is a regular geometrical solid, the external form of which is dependent on its internal structure. All crystalline bodies are so symmetrically constructed that they generally have a tendency to split in certain directions, and this splitting is called crystalline cleavage. The surface planes of crystals have definite relations to certain imaginary lines called *axes*, which are assumed to intersect in the centre of the crystal, and the portions of these lines which are cut off by the surface planes of a simple crystal are called *parameters*. Thus the lines which would touch opposite faces of a cube and intersect one another are parameters. It is generally sufficient to select three of these symmetrical axes to express the ordinary relations of length, breadth, and thickness; but sometimes it is necessary to select four axes.

The following are the six systems of crystallization which are ordinarily adopted:—

1. *Isometric or Cubic System.*—Three parameters, all equal, and at right angles. Examples: The cube, with six square faces, as in fluor spar (fig. 74); and the octahedron, with its sides equilateral triangles (see fig. 75).

2. *Tetragonal or Pyramidal System.*—Three parameters

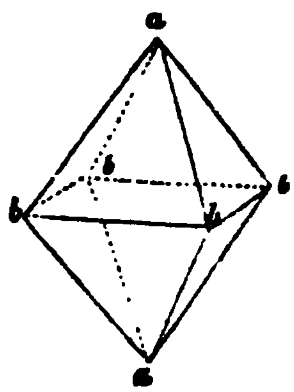

Fig. 77.

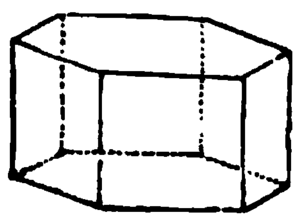

Fig. 78.

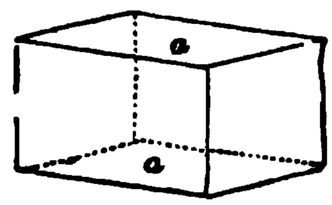

Fig. 79.

at right angles, but only two of them equal. Examples: The rectangular prism on a square base (fig. 76); and the octahedron, with its sides isosceles triangles, as in fig. 77.

3. *Hexagonal or Rhombohedral System.*—Four parameters, three equal and crossing each other at angles of 60° in the same plane, the other perpendicular to this plane. Examples: The six-sided prism on a hexagonal base (see fig. 78), or terminated by a six-sided pyramid, as in quartz.

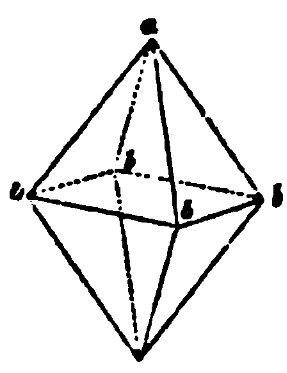

Fig. 80.

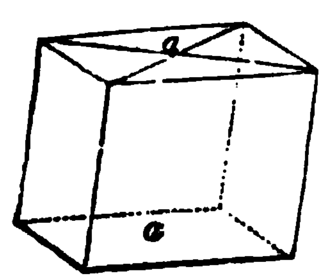

Fig. 81.

4. *Rhombic or Prismatic System.*—Three unequal parameters at right angles. Examples: The rhombic prism (fig. 79), and the rhombic octahedron (fig. 80).

5. *The Monoclinic System.*—Three unequal parameters, two at right angles, and one at right angles to one *only* of these. Example: The oblique rhombic prism (fig. 81).

6. *Triclinic or Anorthic System.*—Three parameters, all

unequal, and oblique to each other. Example: The doubly oblique prism.

The diversity of forms presented by natural crystals is almost infinite; but they may all be referred to one or another of these systems, and may be actually produced by a modification of one of the typical forms above mentioned. Thus, in the first system, a regular octahedron can be ob-

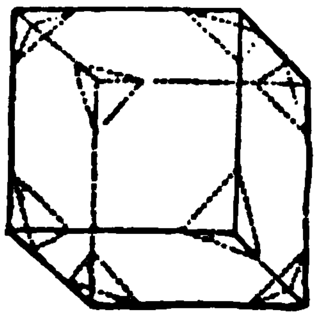

Fig. 82.

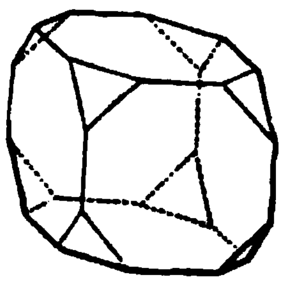

Fig. 83.

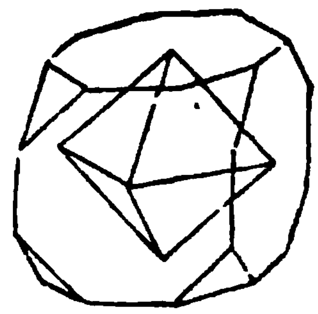

Fig. 84.

tained from a cube in the following manner:—If the eight corners of a cube be regularly truncated, or cut off, as indicated in fig. 82, eight new faces will be produced, resulting in fig. 83; and if the process is continued by cutting away equal portions from these new faces, until the planes meet or touch each other, the regular octahedron will be developed, as shown inside fig. 84.

Similarly, other varieties of form may be produced by

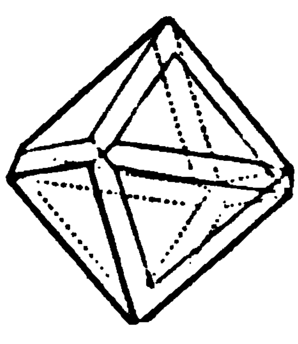

Fig. 85.

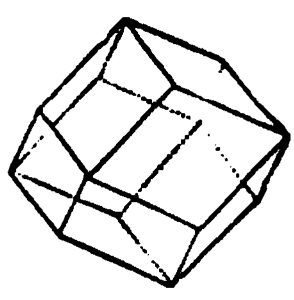

Fig. 86.

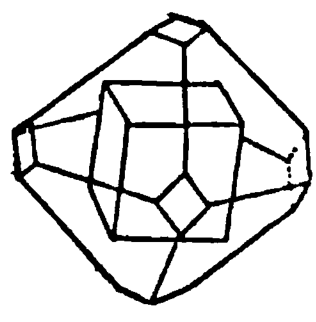

Fig. 87.

the partial or complete truncation of the sides of a cube or octahedron. Thus, if the twelve edges of an octahedron be truncated, we have the form of fig. 85; and, if this truncation be continued till the planes intersect, it will result in the formation of a regular twelve-sided figure, called the rhombic dodecahedron (fig. 86).

But, if the eight corners or angles of the octahedron are truncated, the cube is produced, as shown in fig. 87. Thus,

all three forms may be developed from each other; and similar relations exist between the forms of other systems.

Twinning of Crystals.—Crystals are frequently found which do not appear to belong to any of the regular types above mentioned, or to any direct modification of them. They are, in fact, compound crystals, that is, portions of two or more crystals which have grown together, so that each one is imperfect. An ordinary twin crystal consists of two half-crystals united along a certain plane, but in such a manner that their crystalline axes and faces do not correspond. Such a dual crystal can be formed by cutting a complete crystal in half, turning both halves half round a certain axis (*i.e.* each through 90°) and reuniting them; the plane along which they are reunited is called the composition plane, and the plane parallel to the axis of turning is called the twinning plane. Some form an angle with each other like a knee-joint, and are hence called *genicular twins;* and double genicular twins, thus composed of four half-crystals, sometimes form perfect crosses, which are characteristic of certain minerals.

Other crystals consist of a great number of partially formed crystals all united along parallel planes, this is termed polysynthetic twinning. Such repeated twinning often produces a striated appearance when the crystal is broken along a certain plane of cleavage, and it is always visible when a slice of the crystal is viewed under a microscope with polarized light.

Rock-forming Minerals.—We now proceed to describe those minerals which are the essential constituents of rock-masses. Of the simple elementary substances mentioned on page 308, two only are ever found as minerals, viz., carbon and sulphur. The latter never occurs as a rock-constituent, though it is sometimes rather abundant near volcanoes; the former occurs as a constituent of coal, and as graphite in schist and gneiss. All other minerals are compound substances, and are either binary or ternary combinations, which may be classified in the following manner:—

Binary compounds: A. Oxides, chlorides, fluorides.

Ternary compounds { B. Carbonates, sulphates, phosphates.
C. Silicates.

A.—*Minerals formed of Binary Compounds.*

Silica, when pure and crystallized, is known as *Quartz*, its separate crystals being often called rock-crystal, and sometimes Irish diamond, Bristol diamond, etc. The specific gravity of quartz is between 2·6 and 2·7.[1] The crystals belong to the hexagonal system, their most usual form being a six-sided prism terminated by six-sided pyramids; they are sometimes very large, and sometimes so minute that the mineral appears to be a compact hard stone, which is milk-white when pure. *Amethyst, agate, chalcedony, carnelian, onyx, cat's-eye*, are all mere varieties of quartz, stained of various hues by slight admixtures of iron, manganese, or other colouring matter.

Jasper and *Bloodstone* are impure forms, rendered opaque by the presence of oxides of iron; jasper is generally red, and bloodstone green spotted with red.

Opal and its varieties are hydrated and non-crystalline forms of silica. One of these varieties, called *hyalite*, occurs in the form of minute globules in some sedimentary rocks, and another, called *menilite*, occurs in the form of concretionary nodules, like the flints in chalk. The hydrated form of silica precipitated from thermal waters is called sinter or geyserite; its mode of occurrence has already been described on p. 206. The specific gravity of opal is 2·2.

Flint and *Chert* appear to be mixtures of opaline and chalcedonic silica in varying proportions, but the opaline element is often obscured by the crystallization of the chalcedony.

When quartz occurs in an igneous rock it is usually a greyish, semi-transparent, glassy-looking, irregularly crystalline granule, which cannot be cut or scratched by even the best steel knife, and has no definite cleavage planes.

Oxide of Iron.—Two oxides of iron occur as minerals, the peroxide or sesquioxide (Fe_2O_3), and the less highly oxidized Fe_3O_4.

[1] The specific gravity of a substance is its weight compared with that of the same bulk of pure distilled water at a temperature of 60° F.

Hæmatite (Fe_2O_3) is red or black in colour, but always gives a blood-red streak. When distinctly crystallized it is called specular iron, and belongs to the hexagonal system, and usually occurs in thin tabular crystals, or scales. It often forms fibrous nodules, but many of the beds and nodules of red iron ore which occur among the stratified rocks have resulted from the decomposition of carbonate of iron by the action of water, and hæmatite is therefore frequently a pseudomorph of chalybite.

Limonite is a hydrated form of hæmatite, with the formula $2Fe_2O_3$, $3H_2O$, and generally of a yellowish-brown colour. Yellow ochre and bog-iron ore are varieties.

Magnetite (Fe_3O_4), so called from its magnetic properties, is usually black in colour and streak, and crystallizes in the cubic system, generally in some form of the octahedron. It is frequently met with in igneous rocks, where it is disseminated in small crystals, always black and opaque, and presenting square or triangular sections under the microscope.

Ilmenite, a mixture of the oxides of iron and titanium, crystallizes in rhombohedral forms, and often occurs in thin plates or tables, the outer parts of which are frequently decomposed into a greyish-white substance (Leucoxene).

Iron pyrites, or sulphide of iron (FeS_2), crystallizes sometimes in the isometric and sometimes in the rhombic system; when in the latter, it is called *marcasite*. It is generally of a light bronze colour, and is found disseminated in rocks of many kinds and all ages. In igneous and metamorphic rocks, it occurs in small, sparkling cubic or octahedral crystals. In stratified rocks, the marcasite or rhombic forms are, perhaps, more abundant, especially in dark shales and clays. According to Ebelmen, pyrites is always formed wherever organic matter in process of decomposition acts on the sulphates of sea-water in the presence of ferruginous mud. Thus fossil organisms are often found coated or filled with iron pyrites; and the radiated globular nodules of marcasite frequently contain some small organic nucleus.

Rock salt, or sodium chloride (NaCl), crystallizes in the isometric system, and generally in cubes; it is white when pure, but is usually coloured red, blue, or purple.

Rock salt occurs in extensive beds, which are sometimes of great thickness.

Fluor spar, or calcium fluoride (C_aF_2), crystallizes in the isometric system, and usually in cubes, which are very variable in colour. It occurs chiefly in veins, and can hardly be called a rock-constituent.

B.—*Carbonates and Sulphates.*

Calcite or calc-spar, carbonate of lime ($CaCo_3$), is, after qnartz, the most abundant mineral in nature. Crystallized in the rhombohedral system, with a specific gravity of 2·7, it is called *calcite;* but it also forms rhombic crystals, and is then known as *aragonite*, which is harder and heavier but more easily soluble than calcite. Both effervesce strongly when touched with hydrochloric acid, and this is therefore the usual test for calcareous matter in a rock. Calc-spar always cleaves readily into rhombohedrons; and the name of *Iceland-spar* is given to such as are clear, and are consequently used to exhibit the property of double refraction.

Stalactites and *stalagmites* are formed of successive concentric films precipitated from evaporating water, and the radiating crystalline plates which traverse these concentric coats, without obliterating them, show that the crystallization has been subsequent to their formation. *Dolomite* is a compound of the two carbonates of lime and magnesia; and when the mixture is crystallized, it is known as *bitter-spar*, with a specific gravity of 2·85.

Calcic sulphate, or anhydrite ($CaSO_4$), is better known in the hydrated form of **Gypsum** ($CaSO_1$, 2HO), which usually crystallizes in monoclinic prisms. Gypsum, when transparent, is called *selenite;* when fibrous, *satin-spar;* and some of the compact varieties are popularly called *alabaster*. Gypsum is harder than calcite, and slow to effervesce with acid. It is only found in sedimentary rocks, occurring sometimes in veins and nodules, and sometimes in beds of great thickness, associated with rock-salt. Its formation from the evaporation of sea-water has already been noticed (p. 247). Crystals of selenite are abundant in many clays, either single, or in radiating groups.

Carbonate of Iron, often called *Chalybite* or *Siderite*, is a carbonate of the protoxide of iron ($FeCO_3$), and is another common mineral. It occurs crystallized in veins and beds among crystalline rocks and in the older limestones, having a dull yellow or brownish colour, and a pearly lustre on the cleavage faces. In an earthy state, and mixed with a certain amount of clay or silt, it forms the well-known clay-ironstones which which are so largely worked for iron ore. The heavy brown nodules and septarian stones so common in clays generally consist of mixtures of the carbonates of iron and lime.

Phosphate of Lime is generally foundas a tribasic salt, with the formula of Ca_3PO_4. When crystallized, it is called *apatite*, and occurs in six-sided prisms or tables, belonging to the hexagonal system. Small crystals are not unfrequent in igneous and metamorphic rocks. It is also found massive, forming beds several feet thick.

The phospate nodules, so frequently found in stratified clays and marls, contain from 30 to 60 per cent. of tribasic phosphate of lime, mixed with carbonate of lime and other earthy materials.

C.—*Silicates.*

1. *The Felspar Group.*

The Felspars play a very important rôle in the constitution of rocks. They all consist of silicate of alumina, combined with the silicates of potash, soda, or lime. The names of the most important Felspars are given in the following table, together with their average composition:—

	Silica.	Alumina.	Potash.	Soda.	Lime.	Sp. Gravity.
Orthoclase .	64·6	18·4	16·9	—	—	2·55
Microcline .	64·3	19·6	15·6	—	—	2·54
Albite . . .	68·6	19·5	—	11·8	—	2·62
Oligoclase .	62·1	23·7	—	10·2	4·0	2·64
Andesine . .	59·7	25·6	—	7·7	7·0	2·66—2·69
Labradorite .	52·9	30·3	—	4·5	12·3	2·68—2·74
Anorthite .	43·1	36·8	—	—	20·1	2·75

Orthoclase and Microcline are, therefore, Potash Felspars; Albite is a Soda Felspar; Oligoclase and Andesine are Soda-Lime Felspars; Labradorite is a Lime-Soda Felspar; Anorthite is a Lime Felspar. The first two are the lightest, and the last is the heaviest. One only (Orthoclase) crystallizes in the Monoclinic system, all the others belonging to the Triclinic system; hence the group is sometimes divided into the Orthoclastic and the Plagioclastic Felspars. It has been supposed by some that Oligoclase, Andesine, and Labradorite are not distinct species, but mixtures of Albite and Anorthite in varying proportions.

Orthoclase Felspar generally occurs as a translucent, or semi-opaque, mineral, of a white or flesh-red colour, in monoclinic crystals of an oblong shape, which are frequently twinned. When transparent, with a pearly opalescence, it is called *Adularia; Sanidine* is a similar transparent and glassy variety, forming crystals of a tabular shape, and chiefly occurring in volcanic rocks.

Microcline is closely allied to Orthoclase, even the external crystalline form being similar, though it is really triclinic, and exhibits polysynthetic twinning. Under a microscope and with polarized light fine bands are visible, which cross one another and produce a characteristic pattern.

Plagioclase Felspars of the Soda-Lime series generally form long and narrow crystals, with a bright shining surface, and are usually white or greenish grey. Under the microscope, they may generally be distinguished from Orthoclase by the presence of fine parallel striæ (due to repeated twinning) along some of the planes of cleavage. These are never seen in Orthoclase.

Albite is generally white, sometimes clear and sometimes dulled by partial kaolinization. It occurs separately in some granites, but more often in bands, as in Perthite, or in zones round orthoclase.

Oligoclase and *Andesine* are usually whitish minerals, with a more or less vitreous lustre. They are generally composed of a number of long twinned crystals, which cause a well-marked parallel striation.

Labradorite is the commonest Triclinic Felspar, and forms masses of long twinned crystals, like those of Oligoclase; but usually grey, green, or brownish in colour, with a

vitreous or pearly lustre. Labradorite is slightly soluble in hydrochloric acid; but, under the microscope, it is difficult to distinguish it from Oligoclase, though the former often exhibits a number of fine parallel lines, which cut obliquely across the stripes of colour seen by polarized light.

Anorthite is a much rarer species, though it sometimes occurs in volcanic rocks, such as the Vesuvian lavas. Being a very low silicated Felspar, it is soluble in hydrochloric acid with evolution of free silica.

Nepheline and **Leucite** are light-coloured minerals closely related to the Felspars, but crystallizing in different forms. The one occurs in rather stumpy six-sided prisms, and the other in icosi-tetrahedrons or solids with twenty-four faces. Nepheline is essentially a silicate of alumina and soda with a little potash, while Leucite is a silicate of alumina and potash. Nepheline has a specific gravity of 2·6; while that of Leucite is 2·5. Leucite is common in the lavas of Vesuvius, but has not been found in England, and Nepheline only in the rock called Phonolite.

2. *The Mica Group.*

The Micas are a group of minerals which vary much in composition, but have several properties in common. The crystals, whether belonging to the monoclinic or hexagonal system, split readily into very thin flexible plates, which have a bright pearly lustre and are more or less transparent. They are composed of a mixture of silicate of alumina with silicates of potash, magnesia or lithia, and some iron. They are rather heavy minerals, their specific gravity being from 2·75 to 3·2, and therefore heavier than the Felspars. They vary in their degree of fusibility, but are all easily scratched with a knife.

Muscovite, or Potash Mica, usually occurs in six-sided tabular crystals of a grey greenish or yellowish colour. It is very clear and transparent, and often forms large foliated masses, the separate plates of which are used instead of window glass in Siberia and elsewhere. Commercially it is known as talc, and is used for lamp-shades, etc., but the true talc is a different mineral. Muscovite is very liable to

hydration, and then passes into the white silvery-looking variety called *Margarodite*. *Sericite* is another hydrated mica, silvery-white or pale green, which occurs chiefly in certain metamorphic rocks.

Lepidolite, or Lithia Mica, may be regarded as Muscovite in which the potash is partially replaced by lithia. Its physical properties are similar and its crystalline form the same, but it is usually rose-red or violet in colour, and commonly forms granular masses consisting of numerous scales or folia.

Biotite, or Black Mica, is a silicate of alumina, magnesia, potash, and iron, generally dark green or black. *Lepidomelane* is a variety with less alumina and magnesia, and more iron. It is found in some Irish and Cornish granites, and its colour is black.

3. *Hornblende and Pyroxene Group.*

Hornblende and Augite.—Under these names are included a number of heavy minerals which are closely related to one another, their essential composition being a double silicate of magnesia and lime, the bases being often more or less replaced by iron or manganese. Alumina is often present. They all crystallize in the monoclinic system.

Common Hornblende is a dark green or greenish black mineral usually occurring in long prisms. Its specific gravity varies from 3 to 3·47. The crystals frequently have a fibrous structure and a silky lustre, with external angles of about 60° and 120°, properties which serve to distinguish them from crystals of Augite.

Augite generally occurs in short stout prisms, with external angles which are nearly at right angles to one another. The crystals are usually black or brown, but there are whitish and green varieties, known respectively by the names of *Diopside* and *Sahlite*. Its specific gravity is from 3·3 to 3·5.

Pyroxene is another name for Augite, and *Amphibole* for Hornblende. There is good reason for supposing that they are identical minerals crystallized under different circumstances. Augite has been artificially formed in slags which cooled rapidly. Hornblende has never been so obtained,

and always occurs in rocks which must have cooled slowly. Hornblende has been observed in the thicker parts of a vein of lava exposed in the Val del Bove, Etna, while Augite occurs in the thinner parts of the same vein. Lastly, there is a mineral called Uralite, which has the outward form of Augite, but the cleavage and structure of Hornblende, and Augite can be observed under the microscope in various stages of change into Hornblende.

Diallage is a variety of augite, with a peculiar cleavage, and generally having a pearly grey or brownish lustre; *Tremolite, Actinolite,* and *Asbestos,* are more or less fibrous varieties of Hornblende, containing little or no alumina.

Hypersthene, Enstatite, and *Bronzite* are closely allied minerals, but differ in not containing lime, and in crystallizing in the rhombic system. They are all silicates of magnesia and iron: the first two are generally of a dark greyish brown colour; the last is a dark yellow or brown with a bronze-like lustre, and has much resemblance to Diallage. Its specific gravity is from 3·1 to 3·3.

The following are average analyses of some of the above minerals, but the proportions are not always the same:—

	Dark Hornblende.	Actinolite.	Augite (Diopside).	Bronzite.
Silica.	46	56	51	56
Magnesia . . .	16	24	14	30
Lime.	13	13	21	—
Alumina . . .	12	—	1	2
Iron	12	7	12	12

4. *Peridote Group.*

Peridote is a silicate of magnesia and iron, and is, therefore, chemically related to hypersthene and bronzite, but it contains much less silica, so that the relative proportions of silica and magnesia are generally nearly the same. It crystallizes in the rhombic system, and when found in transparent rhombic prisms it is often called *Chrysolite,*

but it is much more abundant in the form of grains or granular lumps of an olive or yellowish green colour; it is then known as *Olivine*, and is of frequent occurrence in certain igneous rocks, sometimes in such quantity as to be the chief constituent of the rocks called Peridotites.

Serpentine is a hydrated silicate of magnesia and iron; it is generally compact and massive, of a dark green colour, and is greasy to the touch; but it varies much in colour, and is sometimes yellow, brown, red, or black, from the presence of iron oxides. Serpentine, like steatite, results from the decomposition of magnesian minerals, such as Olivine and Bronzite, and gives its name to a particular kind of rock, which is almost entirely composed of it.

The average general composition of Olivine and Serpentine is given below for the purpose of comparison:—

	Olivine.	Serpentine.
Silica.	40·2	38·5
Magnesia	41·7	38·5
Oxides of iron. . . .	18·1	10·2
Combined water . . .	—	12·8

5. *Silicates which generally occur as Secondary or Accessory Minerals.*

Andalusite is essentially a silicate of alumina, though it is seldom quite pure. It crystallizes in the rhombic system, and the larger crystals are often encrusted with and penetrated by scales of mica, which may be a product of its decomposition. The variety *Chiastolite,* so called from the cruciform markings in the interior of the crystals, is usually met with in slates which have been partly metamorphosed by contact with, or proximity to, igneous rock. *Cyanite* is a pure silicate of alumina generally of a pale blue colour.

Staurolite is another alteration product, crystallizing in rhombic prisms which are frequently double genicular

twins, forming a cross, whence its name. It consists of the silicates of alumina and iron.

Garnets consist of silicate of alumina with a silicate of some other base, such as lime, magnesia, iron, and manganese. The percentage of silica is always from 35 to 40, and all the varieties crystallize in the cubic system, and usually in rhombic dodecahedrons. They are generally of a dark colour, red, brown, or black, and are of common occurrence in metamorphic and intrusive igneous rocks. *Idocrase* has a nearly similar composition, but crystallizes in tetragonal forms, is usually lighter in colour, light brown, yellow, or greenish white.

Epidote is a silicate of alumina, lime, and iron; it crystallizes in the monoclinic system, and usually forms long blade-like crystals in radiating groups or nests of a light green colour. It is essentially an alteration product.

Hauyne and **Nosean** are substantially silicates of alumina and soda, with some sulphate of lime or soda; and are related to the garnets. The first is usually of a bright blue colour, and the second of a yellowish grey.

Tourmaline, or Schorl, may be regarded as a combination of a silicate of alumina and iron with a borate. The chemical composition is variable, but it generally contains: silica, 40 per cent.; alumina, 30 to 40 per cent.; boracic acid, 3 to 4 per cent.; with peroxide and protoxide of iron, and protoxide of magnesia. In colour it is greenish or reddish-black, and somewhat resembles hornblende, but may be distinguished by its more resinous fracture, the absence of distinct cleavage, and its greater hardness.

Chlorite appears to be a hydrated silicate of magnesia and alumina, part of the latter being replaced by ferrous oxide; like all products of alteration, its chemical composition varies, and, like mica, it is the name of a group rather than of a single mineral; it generally occurs in earthy or scaly granules of a leek-green colour; sometimes it forms fibrous radiating crystals.

The *Zeolites* are hydrated double silicates having many varieties, to which separate names are given; most of them consist of silicate of alumina with silicates of lime, soda, or potash. They are, therefore, closely related to the Felspars, and may indeed be regarded as hydrated

varieties of the Felspar group. The name Zeolite is derived from their intumescence or boiling up under the blow-pipe as the water is driven off. Mesotype, Prehnite, Chabasite, Analcime, Stilbite, and Thomsonite are among those most frequently met with.

Glauconite is a hydrated silicate of iron, alumina, and potash, of a dull green colour; it is found in cavities of igneous rocks as a result of decomposition, and also occurs in the form of loose grains in marls and sandstones.

Glauconite grains are of frequent occurrence in rocks of all ages, and certain beds called Greensand consist of sandy or marly matter in which so many glauconite grains are distributed as to impart a green colour to the mass. Ehrenberg long ago demonstrated that most of these grains were casts of Foraminifera, and this is confirmed by the observations above mentioned. It is possible that some of the larger and more irregularly-shaped grains may be fragments of the casts formed in larger shells, such as some of the Pteropodous Mollusca; these shells always accompany those of the Foraminifera on the ocean bottom, and their casts in green earth have likewise been met with.

Mr. Sorby, in the course of his microscopical investigations, has found glauconite in the cells of Foraminifera, in the hollow spaces in the tissue of corals and Echinoderms, in holes bored into shells, and, in fact, in all kinds of cavities. Sometimes it occurs in the form of rounded grains or angular fragments which seem to have been formed elsewhere and drifted as sand into their present position.

Talc is a hydrated silicate of magnesia, and its percentage composition is generally as below:—

Silica	=	60 to 62.
Magnesia	=	30 to 33.
Water	=	1 to 7.

When crystallized it is ortho-rhombic, but it usually occurs in a massive condition, splitting into thin laminæ, which are flexible, but not elastic as the plates of mica are. In colour it varies from white to apple-green. *Steatite* or

Soapstone is a coarse earthy variety of talc, usually of a dull white or yellowish colour, and always found in a massive form. Both talc and steatite have a soft soapy feel. *Meerschaum* is a silicate of similar composition.

Pseudomorphs.—Pseudomorphism is the occurrence of one mineral in the crystalline form of another mineral. This may take place either by alteration or substitution. In the one case, the first mineral has been gradually changed into another by the addition or exchange of constituents. In the second case, the new mineral is formed by the gradual replacement of the first mineral particle by particle. Both processes are accomplished by the action of carbonated water, containing solutions of various minerals obtained from the rocks through which it has percolated. Penetrating deeply into the earth, acquiring a higher temperature, and helped by pressure, such water becomes an active agent in altering the constitution of minerals and rocks.

Some of these changes have been imitated in the laboratory of the chemist. Thus "Stein converted a crystal of gypsum (sulphate of lime) into carbonate of lime by leaving it for several weeks in a solution of carbonate of soda at a temperature of 122° F."[1] The sulphuric acid of the gypsum united with the soda to form sulphate of soda, which was dissolved and carried away by the water, while the lime united with the carbonic acid, and remained in the crystalline form of gypsum. The result is only attainable under certain conditions, of which the most essential is slow action, otherwise the original form is lost; but these conditions are eminently fulfilled in all natural operations. Again, Calcite is frequently found as a pseudomorph after other minerals.

The process by which such pseudomorphs are produced is a very important one, since it is precisely that of *petrifaction*, or the mode in which organic forms are mineralized, and their external form, with more or less of their internal structure, preserved for our examination.

[1] Bischof, "Chemical Geology," vol. i. chap. ii.

CHAPTER II.

CLASSIFICATION OF ROCKS.

Meaning of the word Rock.—Before attempting to classify the various kinds of rocks which enter into the composition of the earth's crust, it is necessary in the first place to understand what geologists mean by the term rock. In ordinary language a rock means a hard and massive stone, but geologists know that the character of hardness is an accidental one. The very same beds of limestone may be soft chalk in one place and hard marble in another. The same beds of clay may be harder than the hardest brick in one place, and soft enough to mould into bricks in another; and a sandstone which is hard grit in one part, in another be dug out with a spade. Geologists apply the word "rock," then, as a general term to any considerable mass of mineral matter, whether hard or soft, or whatever may be its form or character, provided it be of sufficient importance to be spoken of as a constituent part of the crust of the earth.

A rock, therefore, may be defined as a mass of mineral matter, consisting of numerous crystalline or fragmentary particles which may belong to one or several different kinds of minerals, and which may be loosely coherent or firmly compacted together.

Texture and Structure of Rocks.—Every kind of rock possesses a special structure and texture; its structure depending on the nature and character of its component particles, its texture on the comparative size of these particles, and the manner in which they are arranged. These qualities of a rock can be determined from small

samples or hand specimens, and the study of them is a part of Mineralogy or Lithology.

When rocks are considered as rock-masses, and studied in their natural positions, other points of difference present themselves; the manner in which they occur, and the shape of the layers, blocks, or masses into which they split, are found to depend largely on the manner in which they have been formed and the materials of which they consist. The study of these relationships is that of Field Geology or Geognosy.

Lithological Classification of Rocks.—It is evident, then, that rocks may be classified either according to their internal structure or their external relations. Let us, in the first place, see to what conclusions a lithological arrangement would lead us. The words in which we have defined a rock suggest a primary lithological difference, whereby all rocks may be divided into two classes. Some are composed of definite *crystalline* particles, which, if not perfect crystals, yet possess some of the external faces and angles of perfect crystals, and have clearly been formed in the position which they now occupy. With these may be grouped certain rocks which consist partially or wholly of a glassy substance. Other rocks consist of a congeries of particles which have not *grown together*, but are *fragments* which have been broken off their parent masses and *brought together* by some external agency; their coherence being caused either by mechanical compression or by a cement of some other substance.

By these lithological differences, therefore, rocks may be primarily distinguished into: 1, *Crystalline;* 2, *Fragmentary.*

Crystalline Rocks.—"All crystals are built up by the successive external addition of minute crystalline particles. It is clear, then, that these particles must have been free to move and arrange themselves; in other words, they must have been the result either of solution in water or other liquids, or of fusion by heat. Whenever, then, we find a crystal or a mineral particle that has an internal crystalline structure, we may feel assured that this structure has been produced either by solution or fusion; in other words, that the crystal has been either dissolved or melted. But if

this be true as regards individual crystals, or crystalline particles, it must also be true of rocks that are made up of such crystals or particles."[1]

It has been already stated (see p. 85) that some minerals are soluble in water containing carbonic acid, and that under certain circumstances they may be deposited directly from such chemical solution. Other minerals, again, such as those which compose volcanic rocks, though practically insoluble in water, can be made fluid by the influence of heat. If then rapidly cooled they solidify into a glass, if slowly they form a crystalline mass. Crystalline rocks therefore are all chemically-formed, and are divisible into two sections: *a*, Aqueous crystalline rocks, and, *b*, Igneous crystalline rocks.

2. *Fragmentary Rocks.*—These consist of particles which have been derived from the disintegration and detrition of pre-existent rocks, or from the decay and disintegration of organic bodies. They may be divided into two groups or sections, according to the manner of their formation, viz.: *a*, Mechanically-formed rocks; and *b*, Organically-formed rocks.

The particles of mechanically-formed rocks bear evident marks of mechanical fracture and attrition, most of them having been more or less rounded and worn by currents of water or of wind, From the broken, chipped, and rounded aspect of their component particles, such rocks are often termed *Clastic*, from κλαστος, broken. This detritive and fragmental origin is very clear in the case of such rocks as are chiefly made up of pebbles or rounded fragments of other rocks, and is hardly less obvious in the case of sand and sandstones. Even igneous rocks have their mechanical accompaniments, in the shape of the dust, ashes, and fragments ejected from volcanic craters, and these may be compacted into solid rocks, whether they fall on the land or into the water.

The organically-derived rocks are wholly or in great part composed of fragments of the hard structures secreted by certain plants and animals, and the manner of their formation has already been fully described. The fragments may be little altered from their original condition,

[1] Jukes' "Manual of Geology," second edition, p. 50.

or else they may be greatly altered and partly mineralized. In the latter case they become allied to the aqueously-formed crystalline rocks.

A lithological arrangement of rocks therefore results in our making four groups, thus:—

1. Crystalline.	*a.* Aqueous. *b.* Igneous.
2. Clastic or Fragmental.	*a.* Mechanical. *b.* Organic.

This, however, is not quite satisfactory, for it classes together aqueous and igneous rocks, and separates the chemically-formed aqueous rocks from their closely allied neighbours of organic origin. It is evidently, then, desirable that we should ascertain whether rocks do not exhibit some differences which are more closely in relation to the conditions under which they have been formed.

Tectonic Classification of Rocks.—Rocks may be classified by the differences in the tectonic structure, or the manner in which they are built up into rock-masses. Those which have been deposited as sediments on the bottoms of seas, lakes, and rivers, are arranged in regular layers, beds, or *strata.* Those rocks, on the contrary, which have consolidated from a state of igneous fusion are always *unstratified* and massive in their structure. Hence we have a primary distinction into *Stratified* and *Unstratified* rocks, and it will also be found that most of the stratified rocks are fragmental (and derivative), while most of the unstratified rocks are crystalline.

Certain rocks will, however, be met with, which present a combination of these characters, possessing a more or less crystalline texture, yet often showing signs of having once been arranged in regular strata. Other rocks exhibit a peculiar fissile structure, which causes them to split along planes which are more or less oblique to the planes of bedding. It is natural, therefore, to conclude that such rocks have undergone a considerable amount of alteration since the period of their original formation, and that new structures have been superinduced upon that of stratification. This kind of alteration is called Metamorphism, and the rocks so affected are called *Metamorphic rocks.*

A tectonic classification therefore, founded upon the structural differences of rock-masses, is a more natural and convenient system of arrangement than that based upon their textural and mineralogical composition. It suggests a twofold division into—1. Stratified rocks; 2. Unstratified rocks, each of these primary groups having a sub-group of Metamorphic rocks.

Genetic Classification of Rocks.—Another basis for the classification of rocks may be found in a primary distinction between (A) rocks which have been found on the surface of the globe by means of the various agencies which have been described in Part I., and (B) rocks which were part of the liquid magma underlying the earth's crust, and have therefore been brought up from below that crust.

It is clear, too, that all the rocks which were formed on the surface during any given period of time, must have been derived from the rocks which existed before that time; and that these must have been either Igneous rocks, or older stratified and Clastic rocks. It is true that fresh supplies of Igneous rock have been brought up from time to time, but the amount of such material erupted during any one period has never been so great as the amount of sedimentary rock formed during that period. Hence in each succeeding period of geological time the quantity of derived and stratified rock must have increased; and inversely, during the earlier portion of the earth's history the amount of sedimentary rock on the crust must have been much less than at present. Finally, we may carry our imagination back to a time when the physical conditions were very different to those now existing, when very little stratified rock had been formed, and when most of the rock at the surface was such as had consolidated from a state of igneous fusion.

From this point of view we may regard the Igneous rocks as parts of the original magma from which the crust was formed, and all other as having been ultimately derived from portions of that magma; so that all rocks may be classed as either *Original* or *Derivative*.

Furthermore, it is obvious that in the lapse of time the structures and component minerals of the members of both these great divisions must be more or less changed by the

influence of the various agencies to which they have been subjected; especially if in the course of their history they have been covered up by thick layers of superincumbent rock, and exposed while damp to a higher temperature and to a great pressure. These are the Altered or *Metamorphic* rocks already mentioned, and it is important to note that these rocks may once have belonged to either of the other great groups, *i.e.*, they may have been either Original or Derivative.

A comparison of the Tectonic and Genetic methods of classification will show that the two arrangements are parallel. The two primary rock-groups in each correspond exactly with one another, for all the Original or Igneous rocks are *unstratified*, and all the Derivative rocks are *stratified*. Both lines of thought also lead to the establishment of subdivisions to include the Metamorphic rocks, or those which are *altered* from their primary condition. From the coincidence of these results we may feel convinced that the most natural and appropriate classification of rocks is into the following groups and sub-groups:—

Primary groups.	Sub-groups.
1. Original, Unstratified or Igneous Rocks.	*A.* Unaltered. *B.* Altered.
2. Derivative, Stratified or Aqueous Rocks.	*A.* Unaltered *B.* Altered.

1. **Igneous Rocks** strictly comprise only those which have consolidated and crystallized from a state of igneous fusion, and none of them present that regular kind of stratification which is characteristic of all rocks deposited in water. They occasionally occur in the form of sheets which are interbedded with truly stratified rocks, and thus simulate strata, but these are either the outspread terminations of very liquid lava-streams, or are intrusive sheets of molten lava which have been injected between two stratified beds.

Igneous rocks are, in fact, either parts of the deep-seated masses of molten material which lay beneath the roots of ancient volcanoes, and were intruded upwards into the rocks through which the volcanic orifices were

opened, or they are portions of the lavas which were actually ejected through these orifices on to the surface of the earth. They are always, therefore, *intrusive* or else *eruptive* rocks.

2. **Derivative or Stratified Rocks** may be fragmental or crystalline; those which have been mechanically formed are all fragmental; those which have been chemically precipitated are generally crystalline, and those composed of organic remains are sometimes partially crystalline. These deposits are often called the Aqueous or Sedimentary rocks, but if we use these terms strictly we should exclude those accumulations which have been formed by the agency of the wind, and which are by some formed into a fourth class under the name of *Aerial* or *Eolian* rocks. These are, however, of comparatively small importance, and need not be excluded from this class if we adhere to the names of Stratified or Derivative rocks. In the same class also should be placed those volcanic ejectamenta which sometimes fall on land and sometimes into the sea, and which are generally more or less stratified. These, however, are sometimes considered as belonging to the Igneous rocks, as resulting from volcanic explosions, though they have not cooled in place from a state of fusion. Mechanical deposits are therefore divisible into three sections: 1, Aqueous; 2, Eolian; 3, Volcanic.

Metamorphic Rocks.—Although these are naturally included under one or other of the primary rock-groups, yet it is often convenient to regard them as forming a distinct group, comprising all rocks which have been so altered in course of time, that either their structure or their mineral composition, or both, are different from that which they first possessed. The characters exhibited by some appear to have been mainly produced by the mechanical stress of vertical or lateral pressure; others have been affected by the chemical action of percolating waters and permeating gases at depths where these influences are assisted by that of heat; so that their ingredients have formed new combinations, and have re-arranged themselves in crystalline forms. All these causes have combined to produce a number of rocks which are more or less altered, and are therefore different from any of the deposits that are now

being formed on or near the surface of the earth. The whole group falls naturally into two sections, viz., the Metamorphic igneous rocks, and the Metamorphic derivative rocks.

Determination of Rocks.—The general relations of rock-masses must be studied in the open country by examining the structure of the rocks which are exposed in pits, quarries, and cuttings of all kinds. It is in this way only that the facts of geology are obtained, and by such observations the student will easily learn to determine at once whether any given rock be Igneous, Stratified, or Metamorphic. Mr. Jukes has well remarked that "a blind man might just as well try to learn the art of painting, as any one attempt to understand geology without personal observation of those objects on the structure of which the whole science depends."

It would be useless, therefore, to burden the reader's memory with minute directions for distinguishing between hand specimens of the three great classes of rocks above mentioned; but the case is different when the necessity arises for distinguishing between the different members of any one class of rocks.

The naked eye, or a hand-lens, will generally inform us whether a rock be crystalline or not, and will give us some insight into the textural arrangement of its component particles; a knife will often guide us in ascertaining what minerals it is composed of by the degree of hardness and resistance they possess.

It is very unsafe, however, to trust in such rough and ready methods of determination, especially in the case of the igneous rocks, and geologists were formerly often led astray by omitting to avail themselves of the more accurate means of determination. These other methods are miscroscopic and chemical analysis.

Microscopic Analysis.—It is now universally admitted that the microscope is of the greatest use in determining the mineral composition, texture, and probable method of origin of all kinds of rocks, and that without its assistance it would be and has been impossible to arrive at a natural classification of the igneous rocks.

For the purpose of examining a rock under the micro-

scope, it is necessary to prepare a thin slice of it. If the rock is a hard siliceous one, it must be sliced by a cutting machine, or a thin chip of it may be taken, ground smooth, and polished on one side. The polished surface is then cemented with Canada balsam on to a piece of plate glass, and the other side is ground down until the section is of the required thinness and transparency. The Canada balsam is then melted, and the slice is carefully pushed off into a dish of turpentine, in which it is washed, so as to remove all traces of the emery powder and other substances used in the grinding and polishing process. The preparation is then mounted on a glass slide with Canada balsam, and overlaid with a thin glass cover, care being taken to remove all air-bubbles from inside.

In the case of softer rocks a slice may be cut with a small saw, one side polished on a sharpening stone (Water of Ayr stone), and cemented on to a slide; the other side may then be rubbed down in water till thin, polished as before, and the dust removed by a brush. It is then covered with a glass slip.

The advantages accruing from the microscopical examination of such slices are especially great in the case of rocks whose texture is so fine and close that their mineral composition could not be ascertained by examination with ordinary hand-lenses. As Dr. Geikie observes: "A rock-section prepared in this way enables us to ascertain with precision the manner in which the different minerals are built into each other, and often throws a flood of light on the origin of a rock and on the subsequent changes which the rock has undergone. It furnishes an opportunity of applying the delicate analysis of polarized light, and thus reveals points of structure in the composition of a rock which could not be ascertained in any other way."

For information regarding the methods of examining rock-slices under the microscope, the reader is referred to Professor Cole's "Aids in Practical Geology," and Rutley's "Study of Rocks."

Chemical Analysis.—Though in the case of crystalline and fragmental rocks a microscopical examination will usually enable us to decide what minerals are present, yet it will not do so in the case of certain igneous rocks (Volcanic glasses),

neither will it reveal the actual proportions of the different minerals or elements present in stratified rocks. It is only by chemical analysis that we can ascertain the ultimate chemical composition of such rocks, and the relative proportion of the different elements they contain. It is in all cases desirable to ascertain the chemical composition of a rock, for it often reveals the presence of minute quantities of certain minerals or elements which cannot be discovered by the miscroscope: and in the case of a glassy igneous rock we can compare the analysis with that of allied crystalline varieties, the mineral constituents of which are already known.

CHAPTER III.

ORIGINAL OR IGNEOUS ROCKS.

A. *Unaltered.*

AS these have solidified from a state of fusion by heat, their present appearance will obviously be the result of two causes: 1, their chemical constitution; 2, the circumstances of cooling. To the former is due the presence of certain minerals and the absence of others; on the latter depends the structural condition of the rock, whether it is a glass, or has assumed a more or less crystalline structure. There are in fact five points of difference among Igneous rocks, which are of special importance; these are:—

1. Mode of occurrence as rocks.
2. Internal structure.
3. Chemical composition.
4. Mineral composition.
5. Specific gravity.

Each of these characters might be made the basis of a classification.

1. **Mode of Occurrence.**—Viewed as rock-masses, they occur in various positions and exhibit different forms, according to the circumstances under which they have solidified. These differences will be described in a future chapter; but as it was formerly customary to classify Igneous rocks according to such differences, they may be briefly referred to here. The divisions made on this basis were: (1) VOLCANIC, or those which had cooled down in the open air; (2) TRAPPEAN, or those which had solidified under comparatively slight pressure, as on the bed of the

ocean; and (3) PLUTONIC, or those which had solidified deep within the earth. The name given to the second group was from a Swedish word, *trappa*, a stair, because the ends of the tabular rock-masses referred to this division had often a step-like aspect. More careful investigation, however, showed that many of the more typical members of this division had solidified in the open air, and that it was impossible to fix on any set of characters which separated them from the ordinary volcanic rocks or lavas, as they are often called. It then became usual to divide the igneous rocks simply into VOLCANIC and PLUTONIC, but here it at once became difficult, owing to the more ready crystallization of the basic kinds, to know where to draw the line. Hence these terms have been abandoned for purposes of precise classification, and are only used as general inclusive names of no very definite meaning, which, however, are often useful.

2. **Structure.**—If the student will examine any masses of igneous rock *in situ*, or any collection of rock specimens, he will soon perceive that they exhibit great differences of texture, some being glassy, some compact and stony, others plainly crystalline.

We know also, as a matter of experiment, that from the same materials, after fusion, may be obtained either a translucent glass or an opaque stone, built up more or less completely of crystalline particles, and by means of the microscope it is found that the matrix, or ground mass, of a rock may be in one of the following conditions:—

A. It may be a true glass (when it is often termed the base). In this case, when a thin slice of it is placed between the crossed nicol prisms of a microscope with a polarizing apparatus, the field remains dark as the stage is rotated. Rocks with a glassy base are said to be *vitreous*.

B. If small, faint, and rather ill-defined patches of light, like the ghosts of crystals, appear and disappear as the stage is rotated, so that no part remains dark throughout a whole revolution, the ground mass is said to be *crypto-crystalline*.

C. If the patches are more definite in shape and rather larger in size, sometimes showing bright tints, so that it is

possible to identify the different component minerals, the mass is said to be *micro-crystalline*. In this state, however, the crystalline grains are often a little indefinite at the boundaries, and do not commonly exhibit the outline of their normal form.

D. If the slide is a mass of well-defined crystals, clearly distinguishable one from another, of which those first solidified generally give indications of their normal external form, the rock is then said to be *crystalline*.

The second of these conditions is in many cases the result of *devitrification*, the gradual change from a vitreous to a semi-crystalline state which takes place in a glass under certain conditions. In such case a crypto-crystalline rock might fairly be regarded as metamorphosed; but seeing that we are not yet able to distinguish satifactorily between cases where the structure is original and where it is secondary, the separation is not generally attempted. Neither is it easy at present to separate rocks with this structure from those of the micro-crystalline group, so that we shall speak of both inclusively as *semi-crystalline*.

Glassy and semi-crystalline varieties are of frequent occurrence among the acid rocks, but are rare and more limited in mass among the basic rocks, and in some instances have not yet received distinctive names.

Ophitic Structure.—This is caused by the occurrence of large crystals of one mineral which include a number of smaller and previously formed crystals of another mineral. Thus in many rocks consisting of felspar and augite, the former has crystallized out before the latter, so that the augite seems to form a ground mass or matrix in which the felspar crystals are embedded. Such rocks were formerly called *Ophites*, but the same kind of structure has since been found in many other rocks, so that the name is only used as a descriptive one. Such rocks often present the appearance known as *lustre-mottling*, the small crystals interfering with the play of the light from the broken surfaces of the large crystals as the specimen is turned in the hand.

Porphyritic Structure.—Conspicuous isolated crystals of any one or more of the component minerals may occur in glassy, semi-crystalline, or crystalline rocks, giving what is

termed a *porphyritic* structure. The name Porphyry was first applied to the dark red or purple rock, speckled with light-coloured felspar, obtained from Jebel Dokhan in Egypt, and largely used by the Romans for decorative purposes. By some means the term became applied in process of time to rocks of the most diverse mineral composition, but exhibiting the same peculiarity of structure, viz., the conspicuous occurrence of one mineral in a more compact matrix. The adjective *porphyritic* is now always used with this meaning, which of course the etymology (*porphyra*, purple) does not sanction, and the name *Porphyrite* has been applied to a definite kind of rock; but the term Porphyry is seldom used as a designation in England.

Crystalline rocks present several textural varieties: they may be coarsely crystalline, like many Granites; they may be finely crystalline and even grained (granulitic); they may be porphyritic; and finally, two of the component minerals may be so intermixed and interwoven with one another by simultaneous crystallization as to produce a curious and easily recognized pattern. This is the structure of Pegmatite or Graphic Granite and hence it is termed *pegmatitic* or *graphic*. Sometimes the matrix of a porphyritic rock has this structure on a minute scale, which is often called *micro-pegmatitic*, but the term *micrographic*, recently proposed by Professor Bonney, is preferable. A rock with a glassy base is said to be *microlithic* when it is crowded with minute crystals or *microliths*.

If the mass of a rock is full of small cavities or vesicles it is said to be *vesicular;* the cavities are often elongated in one direction, and when they are subsequently filled up with some mineral, such as quartz or calcite, the infiltration is called an *amygdule* or *amygdaloid* (*amygdalon*, an almond), and the rock is said to be *amygdaloidal*.

3. **Chemical Composition.**—All the minerals which ordinarily enter into the composition of igneous rocks are silicates, and free silica in the form of quartz is also frequently present. The total percentage of silica which they possess is sometimes as high as 80, sometimes as low as 40, or a little less; hence these rocks are often simply divided into *acid* and *basic*, according as they contain more or less than 60 per cent. of this mineral.

So marked, and, within certain limits, so constant are these differences all over the world, that Bunsen was led to suppose they might be due to the existence of two distinct magmas or liquid layers of different chemical composition beneath the crust of the earth, the intermediate kinds of rock resulting from a mixture of these two magmas in varying proportions. Durocher subsequently extended and elaborated this theory, which may be called Bunsen's law, but connected it with certain physical speculations which are not generally accepted.

Later investigations have shown that different portions of the same rock-mass, and in the case of certain rocks even parts of the same hand specimen, often differ considerably in chemical composition. This is especially the case with porphyritic rocks which have a glassy or crypto-crystalline base; this base may be regarded as the mother liquor which remained after the separation of the crystals from the original magma, and analyses show that it is invariably more acidic than the portion which has crystallized.[1] There is, moreover, a difference, not only in the proportion of silica, but in that of the alkalies, potash predominating in the glassy base, and soda in the crystalline portion.

Commenting on these facts, Mr. Teall remarks: "If after crystallization has progressed to a certain extent in a magma of andesitic [*i.e.*, intermediate] composition, we separate the crystals from the part remaining liquid, the former taken together will have the composition of a basic rock, the latter of an acid rock. It is scarcely possible that this connection can be the result of chance, and if not, it seems to suggest that those variations in the composition of igneous rocks which are expressed by Bunsen's law may be due to differentiation produced in an originally homogeneous mass in consequence of progressive crystallization." (*Op. cit.*, p. 45.) In other words, it suggests that the subterranean magma is homogeneous, and that separation into portions of different chemical composition is effected during its upward passage through the crust.

4. **Mineral Composition.**—The chief mineral components of igneous rocks have already been described, but it is

[1] See Teall's "British Petrography," p. 42.

seldom that many of these occur together in one rock, and certain laws or rules can be laid down regarding their *paragenesis* or association. We can easily understand that when the original molten mass contained a large percentage of silica, its crystallization would give rise to the formation of the more highly silicated felspars, and there might still be a surplus of silica which would remain as free quartz; while in a mass with a low percentage of silica, there might only be sufficient to form the less highly silicated felspars, without any surplus remaining. As a rule, therefore, free quartz is associated with the more highly silicated felspars, such as Orthoclase, Albite, and Oligoclase; quartz may occur as an accessory mineral in company with Labradorite or Anorthite, but never as an important constituent of the rock.

Hornblende also is more commonly found in association with the highly silicated felspars, while Augite is generally associated with the more basic felspars, and with Leucite and Nepheline.[1] Olivine, also, as might be expected, is always associated with the more basic felspars, and sometimes occurs alone with Augite and Enstatite. Hypersthene, a mineral less common than is usually supposed, has the same habit, but is sometimes found with the more highly silicated felspars.

5. **Specific Gravity.**—The specific gravity of a rock depends partly on its crystalline ingredients and partly on the presence or absence of a glassy base. The specific gravity of a mineral in a glassy condition is always less than that of the same substance in a crystalline condition. Thus, quartz crystal has a specific gravity of 2·6, but if fused under the oxyhydrogen blow-pipe it solidifies into a glass with a specific gravity of only 2·2, which is that of the natural silica glasses, Opal and Hyalite. Mr. Teall remarks: "The principal interest which attaches to specific gravity, so far as Igneous rocks are concerned, lies in the fact that it stands in close relationship to their chemical and physical properties. If we compare rocks in the same physical condition, then the specific gravity is seen to vary

[1] But Hornblende and Augite sometimes occur together in the same rock, and Augite is sometimes altered into Hornblende.

with the chemical composition in a tolerably definite manner. . . . . If, on the other hand, we compare rocks of the same composition, then the specific gravity is seen to depend on the physical condition." (*Op. cit.*, p. 48.) His tabulated statement shows that,

1. Specific gravity increases as the silica percentage decreases.

2. Specific gravity decreases as the amount of glass in a rock increases.

Classification.—The systematic classification of igneous rocks is a matter of great difficulty, and all the arrangements which have been proposed are confessedly more or less artificial groupings. Rocks must, of course, be named before they can be classified, and though at first sight it seems easy to define rocks according to the minerals of which they consist, in practice it is not easy, for so variable are the rocks in this respect, that it is difficult to say what minerals may, or may not, occur in one kind of rock. A mineral has a definite form and composition, but a rock is only an aggregate of mineral particles, and though we may give a name to an aggregate of certain minerals, we must be prepared for any amount of variety in their relative proportions, and for the presence of particles of other minerals besides those by which the rock is named.

The only glimpse of a natural order among igneous rocks is that afforded by Bunsen's law, and by what Mr. Teall terms the order of progressive consolidation, that is, the development of different magmas out of one original liquid mass by progressive stages of cooling and crystallization. From this point of view it is clear that chemical composition and specific gravity are points of primary importance, and that mineral differences are only important so far as they indicate difference of chemical composition.

Since, however, the nomenclature used is founded on the presence or absence of certain minerals, it must be possible to classify rocks according to their mineral differences, and such a clasification must make it easier for the student to remember these differences. At the same time the arrangement must be based on such a selection of minerals as will best express the variations of chemical composition, and it

should also accord with the results of observation in the field with respect to the association of rocks with one another.

Finally, attention must be paid to the relative quantities of the different constituent minerals, for the mere presence of quartz grains, or of highly silicated felspars, is not a proof that the rock is a very acid one; that will depend on the quantity present: again, two rocks may have the same mineral ingredients, and yet have a different chemical composition.

In framing the following arrangement of the rocks the author has kept these points in mind, and, so far as the existent nomenclature allows, he has endeavoured to express the recognized scale of chemical composition (from acid to basic) in terms of the mineral constituents. The order of the rock-groups is the same as that given by Professor Bonney in the first edition, but these are now gathered into classes which are defined in such a manner that the reader may at once see on what principles the groups are established.

The subdivisions are made to depend on structural characters, and the terms *Granitoid* and *Lithoid* are adopted to express these: the first including coarsely granular, granulitic, and graphic and micrographic varieties; the second microcrystalline, micrographic, and microlithic varieties. It must be remembered that there are no hard and fast lines between the groups, each group being connected with the others by rocks of an intermediate character.

The minerals mentioned are those which are regarded as essential to the definition of the class. The felspar may be either orthoclase or plagioclase, or it may be partially replaced by nepheline or leucite. The hornblende may, or may not, be associated with augite or mica. These minor differences form subsidiary groups, which will be mentioned when each class is treated in detail.

The glassy rocks are not included in this tabular view, but each of the groups may pass into a volcanic glass when the material has cooled rapidly.

Classification of Igneous Rocks.

CLASS I. Acid Rocks. Percentage of Silica, 66 to 76. Sp. Grav., 2·5 to 2·7. Dominant minerals, Quartz and Felspar. Some mica, hornblende, and augite present.

	Granitoid type.	Lithoid type.
Group A.	Granite.	Quartz, Felsite, and Rhyolite.
Group B.	Tonalite.	Quartz-Porphyrite and Dacite.

CLASS II. Sub-Acid Rocks. Percentage of Silica, 55 to 65. Sp. Grav., 2·7 to 2·8. Dominant minerals, Felspar and Hornblende; Quartz present in small grains.

	Granitoid type.	Lithoid type.
Group C.	Syenite.	Felsite and Trachyte.
Group D.	Diorite.	Porphyrite and Andesite.

CLASS III. Basic Rocks. Percentage of Silica, 40 to 55. Sp. Grav., 2·9 to 3·2. Dominant minerals, Plagioclase felspar, Augite, and Olivine; no Quartz.

Group E. Gabbro, Dolerite, and Basalt.
Group F. The Peridotites and Picrites.

GROUP A.

1. **Granite** is a crystalline compound of quartz, orthoclase, and mica, the particles of all three being generally visible to the eye. The orthoclase is sometimes replaced by microcline, as in parts of the granite of Leinster; and oligoclase and albite are often associated with it. The mica may be muscovite or biotite. When hornblende is present the rock is called *Hornblendic granite;* if augite takes its place we have *Augite granite.* When mica is scarce, and the quartz and felspar are so intergrown that the form has a rude resemblance to Hebrew characters, it is called *Graphic granite*, or *Pegmatite.*

Eurite, or *Micro-granite*, is a fine-grained rock with only a little mica, and is often found in the veins which proceed from a mass of granite. It often contains porphyritic quartz or felspar. The matrix is sometimes micrographic.

2. **Quartz-felsite** has a micro or crypto-crystalline matrix of quartz and orthoclase, with porphyritic crystals of quartz and felspar. The rock has also been called *Elvanite*, but this is not a good name, for the word is only a local Cornish term for a dyke, and many of the elvans do not consist of Quartz-felsite. Many of the crypto-crystalline felsites are only devitrified Liparites.

3. **Liparite, or Quartz-trachyte.**—This is the Volcanic form of a rock which, if entirely crystalline, would be a granite. The ground mass consists mainly of minute crystals of sanidine embedded in a glassy base, with porphyritic crystals, or quartz, or sanidine. Soda-felspar, hornblende, augite, and mica are sometimes present. The rock is often called *Rhyolite*, but it would be convenient to restrict the latter of these names to the more compact varieties, which often give indications of a fluidal structure.

GROUP B.

The members of this group resemble those of Group A, but have a Soda-felspar (Oligoclase, Albite, or Andesine) instead of Orthoclase. Hornblende is generally present, and Quartz always in fair quantity.

1. **Tonalite** is the Granitic form. It takes its name from the Tonale Pass in South Tyrol, near which is a large mass of it: this contains quartz, oligoclase, mica, and hornblende.

2. **Quartz-porphyrite** has the same structure as Quartz-felsite, the felspar only being different, and as many of them exhibit that peculiar felsitic structure which is so generally the result of devitrification, these are probably only altered Dacites.

3. **Dacite** answers to Liparite, the base being glassy and the minerals occurring porphyritically. It receives its name from the ancient Dacia, in which district it occurs. It is also called *Quartz-Andesite*, from the Andes, where it is also found. These rocks are analogous to the quartz-trachyte of the former group. There are also very glassy forms, but these as a rule can only be distinguished by chemical analysis from Obsidian and Pitchstone, and have not yet received distinctive names.

Obsidian and Pitchstone are volcanic glasses, formed by the rapid cooling of Liparites and Dacites. There is no optical difference between the more acid and less acid varieties, which can only be distinguished by chemical analysis. They both consist chiefly of glass, but contain scattered microlites and occasional crystals. They differ from one another thus: *Obsidian* has a very conchoidal fracture and a glassy lustre (being very like dark glass); *Pitchstone* has a more splintery fracture and a resinous lustre. It is not certain to what this fairly persistent difference is due, but probably to the relative abundance of microliths.

GROUP C.

1. **Syenite.**—This rock is usually defined as consisting of orthoclase and hornblende, but it is doubtful whether such a rock exists, and it is at any rate very rare. Moreover a rock of this composition would not be the plutonic representative of Trachyte, which has from 60 to 64 per cent. of Silica. It is necessary to admit the presence of quartz as an essential constituent, though it is only visible by the aid of the microscope. The name is derived from Syene in Egypt, but the rock there is said to contain visible crystals of quartz, and is therefore a Hornblendic granite. Plagioclase is very often present, and mica frequently. *Micrographic Syenite* is a rock with a micrographic matrix of quartz and orthoclase, enclosing porphyritic crystals of hornblende and sometimes of oligoclase also.

2. **Ortho-felsite** is a rock with a felsitic or semi-crystalline matrix, with porphyritic crystals of orthoclase and hornblende.[1]

3. **Trachyte** has the same structure as Liparite, but is without the porphyritic crystals of quartz, the silica being entirely in the glassy base.

SUB-GROUP C^1.—A parallel series is formed by rocks in which the felspar is partly replaced by nepheline. Thus

[1] It must be remembered that many Felsites are only devitrified obsidians, and that some petrologists consider all rocks with a felsitic matrix to be devitrified. A name is wanted for compact crystalline Syenites.

Nepheline Syenite, or Foyaite (from the Foya Mountains in Portugal), consists of Orthoclase, Nepheline, Hornblende, and a little Quartz. *Phonolite* consists of the same minerals, but the quartz is not visible, and the structure is trachytic: plagioclase felspar, leucite, nosean, and mica often occur as accessories, or even in sufficient abundance as to constitute well-marked varieties; augite also may occur. The semi-crystalline and glassy varieties have not received separate names.

SUB-GROUP C².—This forms a portion of the rather limited series of rocks often distinguished as *Mica-traps.* Mica (more commonly magnesia-mica) is always a conspicuous constituent. Some free quartz is occasionally present, and more or less hornblende or augite. The nomenclature of the group is imperfect. It will probably be found convenient to restrict the term **Minette** to the crystalline form, and designate the others respectively *Mica-felsite* and *Mica-trachyte.*

GROUP D.

The members of this group only differ from those of Group B in the relative quantity and size of the included quartz grains.

1. **Diorite.**—As in the case of Syenite, this rock has been regarded in its typical form as a quartzless rock consisting of plagioclase and hornblende. Such rocks do occur, but they cannot be considered as the plutonic equivalents of Andesites, while the majority of the rocks which have been called Diorites contain quartz, though it is not discernible without the aid of the microscope. Mr. Teall's view of the constitution of Diorite is much more logical and satisfactory. He regards quartz as an essential constituent, and therefore excludes the more basic varieties; as he observes, "in the Andesites the silica is present in the interstitial matter, in the holocrystalline rock it separates out as quartz" ("British Petrography"). In many of the plagioclase-hornblende rocks the hornblende is a paramorph after augite (see p. 323).

The felspar is generally oligoclase or andesine, but may

in some cases be labradorite; the rock-structure may be granular or micrographic. If augite be present we have an Augite-Diorite, which passes into Gabbro by a diminution of the quartz. The presence of mica gives a Mica-Diorite. The name *Aphanite* is applied to a fine-grained rock in which the components can only be seen with a microscope.

2 and 3. **Porphyrite** and **Andesite** differ from Quartz-porphyrite and Dacite simply in the absence of free porphyritic quartz, but the Porphyrites are now regarded as only devitrified Andesites.

SUB-GROUP D[1].—**Plagioclase-Nepheline** rocks are not common, and do not occur in Britain. *Tephrite* is an Andesite in which Nepheline and Leucite are present; and *Theralite* is a coarse-grained rock of the same composition. They may be called Nepheline-Diorite and Nepheline-Andesite.

SUB-GROUP D[2].—This contains the remainder of the Mica-trap group, which differs from the Minette group as above described in that a plagioclastic felspar replaces the orthoclase. There is at present the same deficiency in the nomenclature, the term *Kersantite* being applied to the crystalline or more conspicuous representatives.

GROUP E.

The nomenclature of this group, though four members are common, is at present not very precise. The type-rock may be defined as consisting of a plagioclastic felspar, generally labradorite, and of augite, with more or less iron peroxide, and commonly some olivine.[1] Magnesia mica is often present, and sometimes rather abundant. **Gabbro** is a coarsely crystalline rock of granitic structure only occurring in masses, dykes, and veins. In it diallage frequently takes the place of augite, and the name *Norite* is given to a hypersthene-felspar rock. A variety with little augite

[1] As this mineral is frequently abundant enough to become an important constituent, while in other cases it is entirely absent, some have proposed to restrict the term *dolerite* to the former; but the distinction can hardly be maintained.

and much olivine is known as *Troctolite*. A rock in which hornblende wholly or partially replaces the augite is called *Hornblende-Gabbro*. When the two principal constituents are visible to the unaided eye, forming a speckled whitish and black rock, it is called **Dolerite**, and when the constituents are so minute that the rock is black, it is called **Basalt**.[1] No name is thus applied to the (rare) semi-crystalline variety; the glassy form, also rare and limited in thickness (it not seldom exists as a mere coating to ordinary basalt masses), is called **Tachylite**. This is a black or brownish-black glass distinguishable from obsidian chiefly by its greater specific gravity and easier fusibility with the blow-pipe.

SUB-GROUP E[1].—(*a*.) *Nepheline-Dolerite* (or *Nephelenite*). —The rocks of this differ from the last in containing nepheline instead of felspar; there is the same want of preciseness in the nomenclature. The coarser varieties are easily recognized; the finer require microscopic examination. The rock, however, is commonly a little lighter in colour than a felspar basalt.

(*b*.) *Leucite-Dolerite* (or *Leucitite*).—The rocks of this differ from the felspar-basalts in containing leucite instead of felspar. The rock, as a rule, is decidedly lighter in colour than the others, and the augite is sometimes green.

Intermediate forms, containing two or all of the three minerals felspar, nepheline, and leucite, occur.

GROUP F.

The nomenclature of this rather rare group is also in need of revision. The great majority of its members are crystalline, and the rock appears to be generally a deep-seated one. Olivine is the essential constituent, and with it enstatite or augite, or both together, are commonly associated. Hornblende occurs occasionally. There is always some iron peroxide, and small quantities of chrome and nickel are generally detected by analysis. *Lherzolite*[2] is

[1] The term *Anamesite* has been applied to intermediate varieties.

[2] From Lake Lherz in the Pyrenees (Ariège), where the rock occurs.

the name given to a species consisting of olivine, enstatite, augite (variety diopside) and picotite (a variety of spinel). *Dunite*[1] appears to be chiefly olivine and chromic iron.

Picrite contains olivine, augite (or hornblende), with usually some mica and often a little felspar. In *Picrite* the pyroxenic constituent generally rather predominates over the peridotic, and the rock appears to be rather an ancient one. It may be regarded as intermediate between Dolerite and a Peridotite.[2] Here also may be placed *Eulysite*, in which garnets are always conspicuous.

The following are names and terms which are often used, and of which some explanation seems necessary:—*Felstone* and *Greenstone* designate a large group of rocks (most of which would anciently have been included in the Traps) which are too compact in their structure to allow their crystalline condition and mineral constitution to be readily distinguished,—*felstone* including the eurites, felsites, porphyrites, and, perhaps accidentally, some phonolites, and *greenstone* the more compact diorites, aphanites, diabases, and slightly decomposed basalts. The term *Greystone* has been occasionally used for some of the darker felsites, the phonolites, and some of the paler basalts.

Melaphyre is another vague term of dubious advantage. It has been applied to dark compact rocks of considerable geologic age, defined as normally consisting of "felspar (plagioclase), augite, and iron peroxide." Further examination has shown that some of these rocks are *aphanites* or *porphyrites*, but the majority simply rather ancient *basalts*, and so far as the term bears any precise meaning it is equivalent to "probably basalt, certainly old." It has, however, been used so vaguely, though with an air of exactness, that perhaps it is better not to employ it.

Fluid Cavities in the Crystals of Igneous Rocks. —By careful observations on the minute structure of

[1] From the Dun Mountain, New Zealand.

[2] The student will find more complete descriptions of igneous rocks, with illustrations of their appearance under the microscope, in Professor Grenville Cole's "Aids in Practical Geology" (Griffin and Co.), and in Dr. Hatch's "Petrology of Igneous Rocks" (Swan Sonnenschein and Co.).

crystals,[1] Mr. H. C. Sorby has shown that it is possible to arrive at some interesting and remarkable conclusions as to the liquid magma under which the crystalline particles of granite and other igneous rocks were formed. The following is an abstract of his argument:—

When artificial crystals are examined with the microscope, it is seen that they have often caught up and enclosed within their solid substance portions of the material surrounding them at the same time when they are being formed. Thus, if they are produced by sublimation, small portions of air or vapour are caught up, so as to form apparently empty cavities; or if they are deposited from solution in water, small quantities of water are enclosed, so as to form fluid-cavities. In a similar manner, if crystals are formed from a state of igneous fusion, crystallizing out from a fused-stone solvent, portions of this become enclosed, and on cooling remain in a glassy condition, or become stony, so as to produce what may be called glass- or stone-cavities. From these facts he deduced the following conclusions:—

1. That crystals containing only stone- or glass-cavities were formed from a state of igneous fusion.

2. That crystals containing both water- and stone- or glass-cavities were formed in molten rock under the combined influence of highly heated water and great pressure.

Applying these principles to the examination of igneous rocks, Mr. Sorby proves from them the igneous origin of all, with this remarkable result, that the fluidity of the more superficial lavas was a more purely igneous one than that of the deeper seated trappean and plutonic rocks. The minerals of erupted lavas contain stone- and glass-cavities like the crystals formed in the slags of furnaces; but the blocks ejected from volcanoes contain water-cavities as well, the amount of water indicating that they were formed under great pressure and at a dull red heat, when both liquid water and melted rock were present. The crystals of the Cornish elvans and the Cornish and Scotch granites contain both fluid- and stone-cavities, prov-

[1] "Quart. Journ. Geol. Soc.," vol. xiv. p. 453.

ing the presence of water, and perhaps also of gas, as well as the conditions of great heat and pressure.

"On the whole, then," says Mr. Sorby, "the microscopical structure of the constituent minerals of granite is in every respect analogous to that of those formed at great depths and ejected from modern volcanoes, or that of the quartz in the trachyte of Ponza, as though granite had been formed under similar physical conditions, combining at once both igneous fusion, aqueous solution, and gaseous sublimation. The proof of the operation of water is quite as strong as that of heat."

Subsequent investigation has, however, proved that liquid enclosures may be of subsequent formation and due to the partial solution of the crystal, and as it is difficult to distinguish these from original enclosures, the application of Mr. Sorby's results is not always easy.

Pyroclastic Rocks.

The materials ejected from volcanoes being really volcanic rocks may be mentioned here, though they have not consolidated as rocks from a state of igneous fusion, but consist of broken fragments of volcanic rocks; hence they are often called *pyroclastic* materials, from πυρ, fire, and κλαστος, broken.

Agglomerate.—This is a confused assemblage of angular blocks embedded in a paste of finer materials, and is only found in close proximity to the volcano from which all the fragments have been ejected. The blocks are chiefly pieces of lava, but mingled with these are frequently fragments of the local stratified rocks, which have been rent by the outburst of the volcano. A volcanic agglomerate is a terrestrial rock, but if the same materials are ejected into lakes or seas, so that the blocks are more or less rounded and water-worn, a volcanic conglomerate is produced.

Volcanic Ash, Tuff, or Peperino, are names applied to the finer kinds of volcanic detritus; the sand, dust, and powder which is carried to a greater distance from the volcano. They are generally more or less regularly stratified, whether the deposits have been formed on land or on sea-bottoms, but in the latter case the volcanic ashes are

mingled with the materials of ordinary stratified deposits, and sometimes contain organic remains.

Tuffs may be subdivided into two classes, according to the felspathic or pyroxenic nature of the base or ground mass of the rock. The former are called Felstone Tuffs, the latter Greenstone Tuffs.

Felstone Tuff varies in colour from white or grey to yellowish-red or dark brown; in texture it is generally earthy and flaky, and frequently contains broken crystals of felspar, or small fragments of some trachytic rock. Sometimes sand is mingled with this base, and the rock passes into a felspathic sandstone. A nodular concretionary structure is occasionally developed, the size of the nodules varying from that of nuts to that of cannon-balls. The more compact and indurated varieties are not easy to distinguish from felspathic lavas, until the aid of the microscope is called in; this is the case with some of the felspathic ashes or felstone tuffs of North Wales and the Lake district.

Greenstone Tuff is usually dull and earthy in texture, with a prevailing dirty-green or purplish colour. Coarser gravelly varieties also exist, which pass gradually into volcanic agglomerate. In the central valley of Scotland there is a vast quantity of such tuff interstratified with the ordinary sedimentary rocks; Dr. A. Geikie describes it as made up of a paste of abraded dolerite rocks, with fragments of these rocks and of shale, sandstone, limestone, etc. It has a prevalent green colour and is usually well stratified, but a nodular or cannon-ball structure is not uncommon. Similar greenstone tuffs occur in County Limerick, Ireland, and some of these contain fragments of vesicular greenstone (? Dolerite), such as is not known anywhere in the neighbourhood: these fragments are probably portions of the upper scoriaceous surface of the lava which was then rising in the ancient volcano from which the tuffs were ejected (Jukes).

Pumiceous Sand.—Fine comminuted pumice is sometimes ejected from volcanoes and distributed over large areas, forming beds of light grey sand which may be interstratified with volcanic ash and lava, or with aqueous sedimentary deposits.

Altered Igneous Rocks.

Those metamorphic rocks which have resulted from the alteration of Igneous rocks will be described in a future chapter, but a list of them may be given here:—

Gneissic Granite, Schorlaceous Granite, Zwitter-rock, and *Greissen,* are altered granites.

Euphotide is altered Gabbro; *Diabase* and some *Hornblende Schists* are altered Dolerites and Diorites.

Serpentines are altered Peridotites.

Porphyroid and *Schalstein* are altered volcanic tuffs.

Palagonite is generally altered volcanic glass.

CHAPTER IV.

DERIVATIVE OR STRATIFIED ROCKS.

THEIR Origin and Composition.—In Chapter III. we have examined the igneous rocks which come from the interior of the earth, and we have seen that they are essentially siliceous, some of them, especially the granites, containing crystals of pure silica, and all of them containing silicate of alumina. Now pure sand consists of grains of quartz, and pure clay consists of silicate of alumina combined with water. It is obvious, therefore, that clay and sand may be formed by the detrition and destruction of an igneous rock, such as granite, and this process may be actually watched wherever granite rocks are exposed to the erosive action of water.

All the sandy (arenaceous) and all the clayey (argillaceous) deposits, therefore, which are met with in the earth's crust, have been derived from some previously existing rocks, and these older rocks must either have been igneous rocks, or must originally have been derived from some igneous rock.

Similarly the siliceous and calcareous rocks of organic origin have been formed out of the silica and carbonate of lime held in solution by the sea-water; these materials having been primarily derived from the decomposition of the soluble silicates contained in igneous rocks.

The varieties of rock produced by the intermixture of the aluminous, quartzose, and calcareous elements are very numerous. The proportions of these ingredients in any deposit will depend partly on the character of the rocks exposed to erosion in the area whence the chief supply is derived, and partly on the amount of matter contributed

by organisms to the sediment which is accumulating below. Thus the chemical composition of any stratified rock is generally very variable: sands and sandstones frequently contain fragments of other minerals besides quartz; clay almost always contains a certain amount of lime and iron; and many limestones are rendered impure by an admixture of clay or siliceous matter.

Classification and Description.—As already stated, the whole group is naturally divided into two series—A, the unaltered rocks; B, the altered or metamorphic rocks. In the present chapter we shall deal only with the unaltered rocks, and it will be convenient to describe them under the following heads:—

1. Arenaceous rocks.
2. Argillaceous rocks.
3. Calcareous rocks.
4. Ferruginous rocks.
5. Carbonaceous rocks.

1. *Arenaceous Rocks.*

Breccia is a mass of *angular* fragments, the interstices between them being filled either by small débris, sand and dust, or by an infiltrated cement of carbonate of lime or other mineral matter deposited by percolating water. The agencies by which ordinary breccias are formed have been described on p. 191; but Professor Bonney[1] has called attention to another class of breccias, which might be mistaken for the former, but have really been formed in a very different manner. These he terms "*crush breccias*," and believes them to have resulted from pressure or strain acting on a rock generally uniform, but containing weaker beds or portions, which have been crushed *in situ* into fragments of all shapes and sizes. They occur principally in the older rocks, and when the fragments are re-cemented by infiltrated matter they closely resemble an ordinary breccia.

Conglomerate is a mass of consolidated gravel or shingle, the pebbles being rounded and water-worn, and set

[1] "Geol. Mag.," Dec. 2, vol. x. p. 435.

in some kind of matrix which binds them together into a firm rock. The pebbles may consist of any kind of hard rock or mineral which is capable of resisting continued attrition; and siliceous substances, from their great durability, are naturally the commonest constituents. When the rock consists chiefly of quartz pebbles it is called a Quartz-conglomerate; when the pebbles are limestone, it is a Limestone-conglomerate, and so on. The matrix enclosing the pebbles also varies in composition; sometimes it is only sand, and the rock appears to have been consolidated simply by pressure, so that the pebbles may be removed by a slight blow; in other cases the matrix consists of an infiltrated cement, either calcareous, ferruginous, or siliceous, and is sometimes so hard that a blow produces a clean fracture through both matrix and pebbles.

Sandstone is consolidated sand, and the particles are usually quartz. Particles of flint or chert are rare, but occur in some Tertiary sands. Sandstones vary greatly as regards their degree of consolidation, from a mere *sand-rock* which is just compact enough to stand with a vertical face, to a hard and compact *gritstone*, which is capable of being used as a millstone. The size of the grains also varies from the minutest particles of quartz to grains as large as peas, the rock then commencing to pass into a conglomerate.

In the case of sand carried by water the particles are buoyed up in the liquid, their relative weight being less and their friction on the bottom and against one another being proportionately diminished; under such circumstances a great amount of drifting and mechanical action must be required to wear down any quartz fragments into round grains. As a matter of fact, Mr. Sorby finds that the sand brought down by rivers is often very little worn, and that in sea-shore sands the proportion of well-worn grains does not often exceed one-half.

But when drifted and worn by the wind in the open air the amount of friction is necessarily very much greater, and in sands so accumulated all the grains show signs of attrition, most of them being completely rounded, and their surface more or less roughened.

Some of the sandstones associated with shallow-water deposits are doubtless ancient blown sands formed on terrestrial surfaces, and subsequently covered by strata of aqueous origin. But Mr. A. R. Hunt has pointed out that the sand of submarine shoals and sand-banks is kept almost constantly in motion by the action of the waves, and his examination of fine sand from the Skerries shoal in the English Channel showed that a large proportion of the grains were rounded.

There are many varieties of sandstone produced by the admixture of other mineral substances with the quartz grains.

Micaceous sandstone contains flakes of mica which are sometimes so abundant as to cause the rock to split into plates and slabs with glittering surfaces.

Felspathic sandstone contains grains of felspar, distinguishable by their dull white, yellow, or reddish colour, and peculiar fracture, imparting an earthy appearance to the rock. When coarse and resulting from the direct detrition of granitic or gneissic rocks, so that the grains of quartz felspar and mica are angular and plainly visible, it is called *Arkose*. When very fine, so that the constituents cannot be distinguished without a microscope, it may be called a sandy *mudstone*. When compacted by pressure or by the infiltration of a siliceous cement, it is known as *Greywacke*.

Calcareous sandstones.—Of these, three kinds may be distinguished—1, *Cornstone*, a fine-grained rock, probably a calcareous silt cemented by crystalline calcite; 2, *Calcareous grit*, a coarse-grained sandstone, the separate grains of which are cemented together by crystalline calcite; 3, Sandstone, the component grains of which are embedded in large crystals of calcite. These crystals form a kind of mosaic, and each includes a portion of the original substance of the rock.

Argillaceous sandstones, or consolidated silts, are always fine-grained, and generally more or less laminated, so as to split easily along the planes of bedding; they are then called *Flagstones*, and generally contain a proportion of felspathic or micaceous material.

Glauconitic sandstone is one in which grains of glauconite

are conspicuous, giving the whole a greenish tint. The softer kinds are usually called *Greensand*. Some glauconitic sandstones become calcareous grits by the infiltration of a calcitic cement. *Gaize* is a fine-grained micaceous and glauconitic sandstone, occurring among the cretaceous rocks of France and England.

Malmstone, as understood in England, is a siliceous rock, but the silica is chiefly in a colloid state, and derived from an organic source. It is a fine-grained whitish rock, which looks like chalk at a little distance, and it is sometimes calcareous from an admixture of fine chalky matter; but a pure malmstone is light and porous, microscopical examination showing that it consists of very minute globules of colloid silica with numerous broken sponge spicules. Its porosity is due to minute cavities left by the solution of many of the spicules. This rock is often called *Firestone*.

Siliceous sandstones.—Under this head may be placed those sandstones which are compacted into hard rock by a siliceous cement. They are distinguished from quartzite by the fact that the cement is opal or chalcedony, while in quartzite it consists of crystalline quartz formed in optical continuity with the quartz of the original sand. Chalcedony is the cement most frequently found, but opaline cements are known, and an opaline sandstone containing precious opal has recently been found in the interior of New South Wales near Wincannia.

Peldon and *Calliard* are miners' terms applied to beds of hard fine-grained siliceous stone, which have a smooth and even fracture.

Chert is a name applied to any siliceous nodule or layer consisting of earthy or organic particles embedded in a matrix which shows the radiating fibrous structure of chalcedony. Flint differs in having a matrix which is partly chalcedonic and partly microcrystalline. Both have a glassy or flinty fracture.

2. *Argillaceous Rocks*.

Clay may be defined as a consolidated mud which contains sufficient hydrated silicate of alumina to be plastic, or capable of being moulded. *Kaolin*, or porcelain clay, is

nearly pure clay, white and free from iron; its derivation from the decomposition of granite has been described on p. 197. It is now admitted, however, that the decay of orthoclase results in the formation of a hydrated mica as well as of kaolin, both being probably produced simultaneously—one by a total replacement, the other by a partial replacement of the potash by water. Besides this secondary mica, comminuted primary mica seems to be an essential constituent of some clays, and they are generally coloured by oxide or carbonate of iron, or by carbonaceous matter.

Some clays have, doubtless, been formed directly from the waste of granite, gneiss, or other crystalline rock, but many are only the washings of older stratified rocks. Mr. W. M. Hutchings has lately made a careful examination of certain coal-measure clays,[1] and finds that they have resulted from the wear and decay of a granitic rock which consisted of quartz, felspar, and two micas (muscovite and biotite). Minute particles of all these minerals can be seen in the clay under the microscope, but the fine material of the ground mass seems to consist largely of a secondary mica. He did not find anything which could safely be regarded as kaolin, the most minute flakes which could be separated by levigation consisting of mica, and he concludes that even the very finest powdery matter is micaceous. Other clays may be a mixture of kaolin with fine micaceous material, but further investigation is required.

Pipe-clay is a pure white clay, resembling kaolin, but liable to shrink when heated, and consequently not fit for making china.

Siliceous clays.—Fire-clay contains a considerable quantity (often 40 or 50 per cent.) of fine quartz-sand mixed with the silicate of alumina, and a good fire-clay must be free from lime, alkalies, and iron, which act as fluxes; it will then stand a very intense heat without melting. The Stourbridge fire-clay consists of about 64 per cent. of hydrated silicate of alumina, with 33 per cent. of fine sand and 2 per cent. of iron-oxide. *Tile* and *Pottery clays* have a similar composition, but generally contain a larger proportion of

[1] "Geol. Mag.," Dec. 3, vol. vii. pp. 264, 316, and vol. viii. p. 164.

iron. *Fullers' earth* is another siliceous clay, which has the peculiar property of not being plastic in water, but crumbles down into a fine powdery mud. The reason of this is not clearly known. From a recent analysis by Mr. Sanford, it appears to consist of an intimate mixture of the silicates of alumina, iron, lime, and magnesia (50 to 55 per cent.), fine sand (30 to 35 per cent.), and combined water (13 to 15 per cent.).

Gannister is a highly siliceous fire-clay, occurring in the coal-measures, and largely used as a material for the hearths of iron-furnaces.

Marl is a calcareous clay, that is to say, a clay which contains a certain amount of carbonate of lime, and often carbonate of magnesia. When the proportion of carbonates is high, it becomes a chalk marl; when low, it is a marly clay. Strictly speaking, a marl should contain from 20 to 50 per cent. of calcareous matter; but many of the so-called marls contain so little carbonate of lime that they are really only marly clays.

The following are analyses of marls and marly clays:—

	Gault, Surrey, a marly clay (Sanford).	Keuper Marl, Worcester (Voelcker).	Marnes irisées, Lunéville (Voelcker).	Upper Gault, Bedfordshire (Severn).
Silica	46·43	53·62	43·51	38·21
Alumina	18·81	20·53	10·16	3·90
Carbonate of Lime	10·50	7·69	18·92	53·50
Carbonate of Magnesia	·95	5·10	14·40	—
Magnesia as Silicate	·24	1·69	2·10	—
Oxides of Iron	9·97	4·79	5·75	2·00
Alkalies	·07	2·91	·88	—
Water of combination	10·48	4·45	4·24	2·00
	97·45	100·78	99·96	99·61

Shale is the general term for a laminated clay, often called *Bind* or *Blue-bind* by miners and quarrymen; by colliers a carbonaceous shale is called *Batt*.

Boulder clay is a clayey deposit, full of stones and boulders, generally unstratified, and due to the agency of ice.

3. *Calcareous Rocks.*

The processes by which calcareous rocks are formed have been described in Part I., pp. 238 and 273. These rocks may be roughly divided into two classes: (1) those which are largely formed of organic débris—*i.e.*, fragments of the shells and skeletons of organic bodies; and (2), those which have been formed by the precipitation of carbonate of lime from a state of aqueous solution. Those which come under the first head are by far the most numerous and important, but the proportion of recognizable organic fragments in such rocks varies greatly, and the interstices between these fragments are generally filled up by fine calcareous mud or by a subsequent infiltration of calcite.

The fine powder or paste which forms the ground mass of many limestones may itself be partly a chemical precipitate (see p. 277), hence it seems probable that nearly all calcareous rocks contain a large amount of chemically formed carbonate of lime, either of contemporaneous or subsequent formation, and with this small quantities of silica or iron are often mingled.

Many calcareous rocks are very pure, but mechanical admixtures of clay or sand with the calcareous matter are of course frequent, and give rise to sundry lithological varieties.

A Limestone may be defined as a calcareous rock which is sufficiently coherent and consolidated to be called stone, though it may be soft or hard. Like all other rocks, limestones exhibit various degrees of consolidation; some are compacted by pressure, others by the infiltration of a crystalline cement, and, in some cases, the whole rock has assumed a crystalline structure, which completely obscures its organic origin. The varieties of limestone are consequently very numerous, and their differences appear to depend upon the three following circumstances:—

1. The nature of the organic particles, whether derived from Corals, Mollusca, Crustacea, Echinoderms, or Foraminifera.

2. The proportion of other mineral matter mingled with these.
3. The extent of subsequent consolidation by pressure, infiltration, and crystallization.

The following are some of the more important and common varieties of limestone.

Shell limestone is a rock in which the shell-fragments are large and conspicuous, so that the nature of the organic remains is easily ascertained. Occasionally some particular fossil is so abundant as to give its name to the rock; thus we have the *Pentamerus* limestone of Shropshire, the *Orthoceras* limestone of Sweden, the *Hippurite* limestone of Southern Europe, and the *Nummulite limestone* from the large Foraminifera called *Nummulites*.

Crinoidal limestone is composed of broken fragments of the Echinoderms called *Crinoids* or *Encrinites*, and *Coral limestone* is similarly composed of the broken fragments of corals and nullipores (see p. 284).

Chalk is a white, earthy, fine-grained limestone, sometimes soft and friable, sometimes hard and compact. Chemical analysis shows that it is very pure, the whiter varieties containing from 96 to 98 per cent. of carbonate of lime. Microscopical analysis shows that it consists partly of the minute shells of Foraminifera, partly of the broken fragments of the shells of bivalve Mollusca, the fibrous shells of a particular genus called *Inoceramus* furnishing the greater number of these fragments. In some beds of English chalk these shell-fragments are quite equal in bulk to that of the Foraminiferal remains, and in weight would far exceed the latter. *Tertiary chalk* from Barbados and the Pacific (New Britain) has a similar composition, but the shell-fragments are fewer and are derived from thin shells, *not Inocerami*.

Oolite, or Roe-stone, consists of a number of small round particles, about the size of the eggs in the roe of a cod-fish. These little grains consist of carbonate of lime arranged in successive concentric coats round some minute particle of foreign matter which forms a nucleus. This nucleus may be a particle of sand, or a minute fragment of coral or any such substance. Some oolites simply consist of these

spheroidal grains, loosely agglutinated to one another; in others the interstices are filled up by fine-grained, calcareous mud; others are cemented by an infiltration of crystalline calcite. They usually form freestones, or rocks which can be cut with equal facility in any direction; Bath-stone is a familiar example. The occurrence of oolitic rock in recent coral-reefs has been mentioned on p. 285. *Pisolite* is a variety in which the grains are as large as peas.

Lithographic limestone is a very pure, fine-grained limestone, containing as much carbonate of lime as the purer varieties of chalk, and equally free from grit and other impurities, but very much harder than chalk.

Marble.—This name is popularly applied to any compact limestone which is sufficiently hard to take a polish, but geologists confine the term to limestones which are in a highly crystalline condition, owing to contact with igneous rock, or other causes as yet little understood.

Siliceous limestones contain, as their name implies, a certain amount of silica diffused through the calcareous mud. They are always fine-grained and hard, breaking with a splintery or conchoidal fracture. Limestones which contain a small amount of silica and alumina afford the materials of hydraulic cement, and are called *Hydraulic limestones.* According to Gmelin, hydraulic cement is a pasty admixture of lime, silica, and water, which when immersed in water is gradually converted into a hydrated silicate of lime. When the silica is in the larger proportion, the stone is called a *Cherty limestone.*

Argillaceous limestone contains a variable admixture of clayey matter. Some varieties of hydraulic limestone would come under this denomination.

Marl is a term which is used very loosely; some deposits being called marl which are really clay (see p. 364), and others being generally called clays which are really marls. *Chalk-marl* is a very calcareous marl, or impure chalk. *Clunch* is a hard and tough variety of marl. A marly limestone is often called a *Marlstone.*

The following are analyses which show the composition of some of the rocks above mentioned:—

Analyses of Compact Limestones.

	Lithographic Limestone.	Bath Oolite.	Devonian Marble.	Wenlock Limestone.
Carbonate of Lime	96·24	94·59	94·00	74·64
Carbonate of Magnesia	·21	2·50	·08	2·51
Silica	} 2·02		3·30	20·03
Oxides of Iron and Alumina . . .		1·20	1·90	2·38
Water and loss. .	1·53	1·71	·72	·09
	100·00	100·00	100·00	99·65

Analyses of Chalky Limestones.

	Upper Chalk, Kent.	Middle Chalk, Westbury.	Grey Chalk, Farnham.	Chalk Marl, Wiltshire.
Carbonate of Lime	98·52	93·62	85·95	70·80
Carbonate of Magnesia	·29	·18	1·18	1·72
Sulphate of Lime .	·14	·13	·10	2·65
Silica	·65	1·11	9·37	22·80
Oxides of Iron and Alumina . . .	·40	2·67	1·94	1·02
Alkalies and loss .	—	2·26	1·47	1·00
	100·00	99·97	100·01	99·99

Magnesian limestone, or *Dolomite*, is of variable chemical composition; the ingredients are the carbonates of lime and magnesia, but the proportions of these minerals vary very much. A dolomitic or magnesian limestone generally has a gritty texture, and is often cellular or cavernous; its colour is usually some shade of yellow or brown. When regularly bedded it often makes a good building stone, but occasionally it has a tendency to assume nodular and con-

cretionary forms. These sometimes resemble cannon-balls scattered through the rock, and are sometimes grouped together like bunches of grapes. This nodular structure may be seen in the cliffs of magnesian limestone near Sunderland, whence balls from three to six inches in diameter may be extracted; these consist mainly of calcic carbonate in crystals which radiate from the centre, while the horizontal lines of lamination may be traced across them, showing that the nodules are of subsequent formation.

We have seen (p. 287) that some dolomites may have been formed by direct chemical precipitation, but others have undoubtedly been produced by the subsequent *dolomitization* of ordinary limestone. It is probable that this dolomitization is effected by the percolation of water containing some salt of magnesia in solution. Cases occur where a portion only of a limestone mass has been thus altered, the dolomite occurring as a broad rib bounded by joint planes; in other cases a single bed, or group of beds, has been dolomitized; the mode of alteration being doubtless determined by the comparative facility with which water could percolate either down the joints or along the bedding planes of the rock.

It has been thought that the peculiar structure of magnesian limestone is due to the diminution in bulk consequent on the conversion of part of the carbonate of lime into dolomite. This substance is denser than calcite, having a specific gravity of about 2·9 compared with 2·7 of calcite, and its formation may produce a general contraction of the rock-mass, which results in the development of the cellular structure.

Tufaceous limestone.—This is always of fresh-water or terrestrial origin, and has the same variable structure as recent tufa or travertine (see p. 204), being sometimes friable and cellular, sometimes hard and rough, and sometimes partly crystalline.

Bituminous limestone is a black rock containing much carbonaceous matter derived from the decay of animal or vegetable matter. Many dark limestones emit a fetid smell when struck by a hammer, probably from the presence of animal matter, and the smell is sometimes so

strong that the quarries can be smelt at a distance of a hundred yards. To such fetid limestones the Germans give the name of *stinkstein*.

Glauconite marl or limestone is one containing numerous grains of the mineral called Glauconite. The basement beds of the chalk in the southern and central parts of England are glauconite marls. *Bargate Stone* and *Kentish Rag* are glauconite limestones.

Gypsum, or hydrous sulphate of lime, occurs in layers and beds of various thicknesses. The thin beds and veins are generally fibrous, being made up of long acicular crystals, which are disposed at right angles to the bounding surfaces; but in thicker beds the texture is often granular. The gypsum of Montmartre, from which plaster of Paris is derived, is chiefly granular, each bed being composed of many layers of little crystals, slightly differing in colour and texture, giving the mass a laminated appearance. In an instance observed by Mr. Jukes at Montmartre, a bed composed of such crystalline layers was traversed by the cleavage planes of a subsequent and more massive crystallization. *Anhydrite*, the non-hydrated form of calcium-sulphate, is sometimes found, but when exposed it absorbs water and becomes gypsum.

Although not a calcareous rock, it is convenient to consider rock-salt here, as it does not come into any of the other classes.

Rock Salt, or chloride of sodium, is generally found in lenticular bed-like masses of greater or less extent and thickness. In England and Ireland it commonly occurs as a rudely crystalline mass, which is frequently stained red by the admixture of ferruginous clay; the beds are often from 60 to 80 feet thick, but probably thin out in all directions. In the Carpathian mountains there are a series of salt-beds, which in some places make up a thickness of 1,200 feet, and extend for a distance of 500 miles.

4. *Ferruginous Rocks.*

Ironstone is a popular name for any rock which contains sufficient iron to be worth smelting, consequently there are as many different kinds of ironstone as there are of lime-

stone, and the iron is sometimes in the state of carbonate and sometimes of oxide.

Argillaceous ironstone, or clay ironstone, consists mainly of carbonate of iron (60 to 65 per cent.), with varying amounts of carbonate of lime, clay, and silt. The coal-measure ironstones are of this kind; they occur in nodular layers and irregular beds, from a few inches to several feet in thickness. The large, heavy nodules or concretions which occur in many clays contain much carbonate of iron. The Blackband ironstones of Scotland consist of carbonate of iron mixed with 15 or 20 per cent. of carbonaceous or coally matter, so that they can be calcined with very little fuel.

Siliceous ironstone.—When the iron-ore is mixed with sand we have a siliceous ironstone or a ferruginous sandstone, according to the relative proportions of the two materials. Such a rock is the *Northampton ironstone*. This now consists of hydrated peroxide of iron and siliceous matter; but the iron was originally in the form of carbonate, and has been oxidized by the action of percolating water charged with carbonic and crenic acids (see p. 90).

Ferruginous limestones.—These are rocks which have originally consisted of the carbonates of lime and iron in varying proportions, but the action of percolating water has always oxidized more or less of the iron-carbonate, so that the surface portions of the rock are decomposed and reddish-brown in colour; but when followed below a cover of other rocks, or met with in boring or sinking, such a rock is bluish-grey in colour. The *Marlstone rock* of the Lias is a ferruginous limestone of this kind, and is often sufficiently rich in iron to be worked. In the Cleveland district of Yorkshire it contains from 60 to 70 per cent. of iron-carbonate. The *Tealby ironstone* (Lincolnshire) is a marlstone which is full of small brown oolitic grains of limonite, and where the stone is soft and less rich in iron it is locally called *Roach*.

Hæmatite sometimes occurs in the form of beds and irregular masses, and is then entitled to be called a rock; they generally occur in limestones, and seem to replace portions of this rock, the iron having been introduced in solution. In many cases the limestone may have been

first converted into dolomite. Sometimes it forms very large masses, such as that of the mountain called Pilot Knob in the Rocky Mountains.

Chalybite and *Magnetite* also sometimes occur in masses large enough to be called rocks, and occasionally form the substance of whole mountains. The marlstone rock above mentioned is often 20 to 30 feet thick, and the Erzberg at Eisenerz, in Styria, which rises 2,600 feet from its base, consists almost entirely of chalybite. The Magnetberg in the Ural Mountains is wholly composed of magnetite, and Gellivara in Lappmark, a mountain 2,000 feet high and three miles long, also consists of magnetite.

5. *Carbonaceous Rocks.*

Coal may be defined as an accumulation of mineralized vegetable matter, which has lost much of its oxygen, and has been compressed into a rocky substance. In chemical composition it differs from wood chiefly in having a less proportion of oxygen and a greater proportion of carbon. In wood, the average proportions of carbon and oxygen are respectively 49 and 43 per cent. of the whole mass.

Lignite is altered and compressed wood in the first stage of becoming converted into coal; it is often quite black, but still soft and woody, and contains from 22 to 25 per cent. of oxygen.

Brown coal may be regarded as compressed and partially carbonized peat, but there is often much lignite mixed with it. In colour it is generally brownish and soft when quarried, but sometimes it is compact and nearly black. Its vegetable origin is generally apparent.

Cannel or *Parrot coal* is compressed vegetable matter which has lost still more oxygen, retaining only some 10 or 12 per cent. It has a platy fracture, and is generally bright and shining, but sometimes dull and earthy, its appearance depending on the amount of dust and ash it holds. It does not soil the fingers, and always burns brightly, hence the name of "cannel," or candle-coal. It often takes a good polish, and can be worked like *jet*, which is, in fact, a similar substance found in smaller quantities.

Common house-coal is hard and compact, though often

brittle, breaking generally into cuboidal lumps. There are three marked varieties: (1) *Caking coal,* which runs together into clinkers or cinders: the Newcastle coals are of this kind. (2) *Splint* or *Hard coal,* common in Scotland, not easily broken or kindled. (3) *Cherry coal,* which is lustrous, easily breakable, quickly kindled, and does not cake. To this variety most of the Staffordshire coals belong.

Anthracite or *Stone-coal* is very hard and heavy, with a glossy lustre, and a more completely mineralized appearance.

The transition from Lignite to Anthracite by the gradual removal of the oxygen is shown in the following table:—

	Lignite.	Earthy Cannel Coal.	Splint Coal.	Caking Coal.	Anthracite.
Carbon	65·3	66·4	75·58	84·28	91·44
Hydrogen	6·6	7·54	5·50	5·52	3·46
Oxygen	} 25·3	10·84	8·33	6·22	2·58
Nitrogen		1·36	1·13	2·07	0·21
Ash	2·1	13·82	5·46	1·89	2·31

Bitumen or *Asphalt* is a light, brittle, black, or nearly black mineral, some varieties much resembling cannel coal, but differing in being soluble in turpentine and in melting under the influence of heat. It contains much more hydrogen than coal, and belongs to the group of substances known as Hydrocarbons. It occurs in lenticular lumps and masses among shales and flaggy sandstones, and sometimes forms layers of considerable extent, as in the island of Trinidad (West Indies).

Petroleum is a liquid hydrocarbon, some varieties being thin and clear, others thick and viscid, like tar. Being liquid, it is not confined to the rocks in which it was first generated, but makes its way along cracks and fissures, and even rises to the surface in the manner of an artesian spring. Hence it occurs in rocks of all kinds and ages. Some shales and sandstones hold large quantities of it,

and shale which is so saturated as to yield oil on slow distillation is known as *oil-shale.* A good oil-shale may be known by the peculiarity that parings made with a knife curl up as they are cut. Oil-shale is generally rich in organic remains, especially of fishes and molluscs, and it seems probable that in most cases the oil has been derived from the decay of these creatures. The richer shales yield from 30 to 40 gallons of mineral oil per ton of shale.

CHAPTER V.

STRATIFICATION.

THE **Formation of Strata.**—The descriptions given in the first part of this book of the manner in which deposits are formed in the rivers, lakes, and seas of the world are really descriptions of the formation of strata, and we have throughout assumed that the reader has a general comprehension of what is meant by lamination and stratification, so that it is not now necessary to enter into any elaborate definition of these terms.

It is sufficient, therefore, to say (1) that stratification is the arrangement of deposited matter in regular layers or strata; (2) that lamination is a structure possessed by certain strata which separate into still thinner layers or laminæ, each of which is a separately deposited film of sediment.

Laminæ and strata are formed in exactly the same way, by the deposition of successive layers of material, and the difference between them is simply that of the thickness accumulated between the pauses of deposition; these pauses being marked by the planes along which they separate.

All stratified rocks, whether coarse or fine in texture, split into beds or strata, which may be of any thickness from an inch to several feet; but it is only rocks of fine texture which split into laminæ. In some cases fifty or sixty separate laminæ may be counted in the thickness of an inch; in others the laminæ are only discernible as bands of colour, or as forming a kind of grain in the rock, so that it splits most readily in a direction parallel to the planes of bedding.

These general facts of lamination and stratification are

represented in fig. 88, where seven different beds succeed one another in regular order; the dotted beds being meant for sandstones, the lined beds for shales, and the plain beds at the top for limestones. In the limestones no lamination is visible; in the sandstones it is just visible by the arrangement of the component particles along lines which produce a definite "grain"; lastly, the beds of shale are fissile or divisible into separate laminæ.

Since in one bed or stratum of shale there are a certain number of laminæ, say, for instance, it is composed of fifty such laminæ, and since each of these was separately deposited, it follows that so many separate acts of deposition

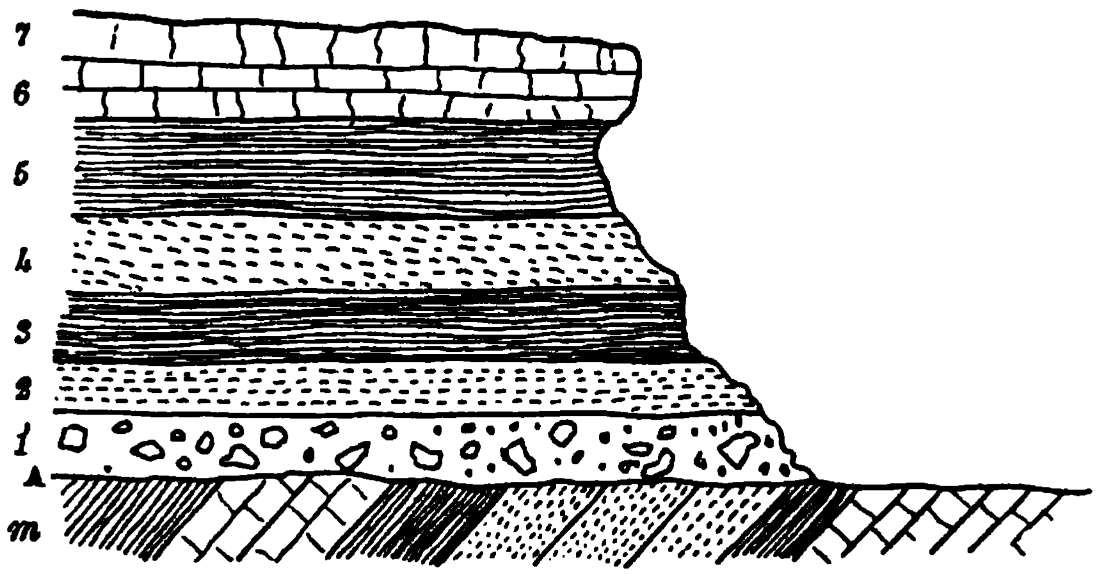

Fig. 88. Lamination and Stratification.

took place in the making of that single stratum, and that its production was a process involving a considerable amount of time.

Lamination does not depend on the fineness of the material, nor altogether on the presence of flaky minerals such as mica, but chiefly on the manner in which the material was spread out. The want of lamination may be due to the continual subsidence of fine sediment for a long time without any pause in the deposition, so that the whole forms an inseparable bed or mass of clay or marl; or it may be due to the rapid accumulation of a large quantity of sediment at once, the result, perhaps, of a single flood, as in the case of some beds of sand or gravel.

Length of the Intervals between Beds.—The intervals or periods of non-deposition marked by the planes of separation between beds must vary considerably in

length. The interval between the formation of two contiguous beds of similar lithological character is not likely to have been so long as that between beds of different lithological character. In a series of sandstones, for example, the pauses between the deposition of the successive beds may not have been longer than the intervals between successive tides, and it is clear at any rate that the same physical conditions which favoured the deposition of the first beds were continued during the deposition of the succeeding beds.

On the other hand, in such a series of strata as those represented in fig. 88, where each superimposed bed is different to that on which it rests, the intervals between the beds represent pauses during which some change took place in the surrounding physical conditions. Thus, in the case of a shale resting on a sandstone, we must suppose some alteration to have occurred either in the velocity of the currents, or in the geography of the district. The change may have resulted from a diminution in the strength of the current, so that it could only transport mud to the place where it previously brought sand; or from the introduction of a fresh current carrying mud only instead of sand; or, lastly, from the depression of the land whence the supply was obtained, so that the distance from the shore was increased, and only finer sediment could be deposited.

In the case of a sandstone succeeding shale, we should assume the reversal of one of the causes above mentioned, either an increase in the velocity of the current, or the ingress of a sand-bearing current, or the general elevation of the coast, which would probably change the set of the currents altogether. A limestone resting either on shale or sandstone would lead us to conclude that similar changes were carried on to a still greater extent, till they resulted in the cessation or diversion of all mud-bearing currents, and a long period of rest or slow subsidence ensued, during which the limestone was slowly formed by the accumulation of shells and other calcareous structures secreted by the various animals which lived in the clear waters.

A shale overlying a limestone is, of course, the reverse of the case just mentioned, and the invasion of clear water

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The lowermost beds in this quarry consist of the Portland Oolite (1, 2), full of marine shells; upon this marine limestone rests a thin seam of black earth (3), full of vegetable remains. Above this are beds of limestone (4), containing fresh-water fossils, and this is succeeded by a thicker seam of vegetable earth (5), full of the roots, trunks, and branches of ancient trees; this is locally known

Fig. 90. Purbeck Beds at Portland. Total thickness about 30 feet.

as the "dirt-bed." Above come finely laminated limestones (6, 7, 8), of fresh-water origin.

The most remarkable fact here exhibited is the position of the trees in the dirt-bed, for they are still erect in the position of growth, with their roots in the vegetable soil and their trunks extending into the limestone above. The interpretation of these facts is as follows:—

The sea-bottom, represented by beds 1 and 2, was elevated into dry land on which many kinds of plants grew

in great luxuriance and contributed their remains to the formation of the vegetable mould (3). A change then occurred which converted this part of the terrestrial surface into a fresh-water lake, and led to the deposition of the limestone (No. 4). This lake, however, gradually silted up, and part of it passed into the condition of a swamp or fen, which was favourable to the growth of an extensive forest. The lapse of time represented by the accumulation of this little bed of 12 inches in thickness must be very great: time for many generations of trees to grow, flourish, and decay.

Dr. Mantell has thus described the scene presented by the quarry in 1832, when a large surface of the dirt-bed had been cleared for removal.[1] "The floor of the quarry was literally strewn with fossil wood, and before me was a petrified forest, the trees and the plants, like the inhabitants of the city in Arabian story, being converted into stone, yet still remaining in the places which they occupied when alive. . . . . The upright trunks were generally a few feet apart, but 3 or 4 feet high; their summits were broken off and splintered, as if they had been snapped or wrenched off by a hurricane at a short distance from the ground. Some were 2 feet in diameter, and the united fragments of one of the prostrate trunks indicated a total length of from 30 to 40 feet. In many specimens, portions of branches remained attached to the stem. The external surface of all the trees I examined was weather-worn, and resembled that of posts and timbers of groins or piers within reach of the tides, and subjected to the alternate influence of the water and atmosphere; there were but seldom any vestiges of the bark."

It is plain that the forest was destroyed by the depression of the district, and the consequent influx of the lacustrine waters. Layer after layer of calcareous mud was deposited over stems and roots, until the old forest was buried under many feet of limestone. To accomplish this change must have taken a considerable length of time.

The Law of Vertical Succession or Superposition.—The simple facts which have just been described

[1] "Wonders of Geology," seventh edition, p. 400.

form the basis upon which the whole fabric of historical geology is founded. In any succession of beds each one represents the conditions which prevailed over a certain area for a certain length of time; the lowest is the oldest, the uppermost is the newest, and the relative age of the others is indicated by their relative position. In order to mark this fact, geologists are in the habit of numbering such a succession of strata from below upwards, so that if the beds represented in fig. 88 were observed in a cliff they would be described as follows:—

No.	Beds.	Thickness.
7.	Compact limestone . . .	3 feet.
6.	Argillaceous limestone . .	1 „
5.	Laminated shale	4 „
4.	Flaggy sandstone	3 „
3.	Laminated shale	3 „
2.	Fine-grained sandstone . .	2 „
1.	Sandy conglomerate . . .	3 „

Alternation and Inter-stratification of Beds.—A series of beds which have been uniformly and consecutively deposited generally preserve a certain regular order in their vertical succession. Beds of very fine and very coarse texture are seldom in contact with one another, except where the lower stratum has suffered erosion before the deposition of the upper stratum, which then rests upon a surface of denudation. In a natural and normal series, therefore, deposited during a period of continued depression, conglomerates are covered by sandstones, sandstones are succeeded by shales or clays, and these are followed by marls or limestones, as in fig. 88.

Similarly, if a marine area, on the bottom of which calcareous deposits have been formed, is affected by a movement of elevation, the clear water is first invaded by gentle currents which introduce finely divided mud before it is traversed by those of sufficient strength to carry the coarser material of sand. Pauses in this process, or alternate movements of elevation and subsidence, will of course occasion corresponding alternations in the succession of deposits.

It is seldom indeed that the change from one kind of deposit to another is sudden and complete; where a sand-

stone passes vertically into a shale, there is usually a space where beds of shale and sandstone alternate with each other, or where laminated sandstones form a passage from the arenaceous to the argillaceous strata. Similarly, where a shale is succeeded by a limestone, the lower beds of the latter are usually separated by layers of shale. Two kinds of rock occurring alternately in this way are said to be interbedded or interstratified with one another, as in the case of the limestones and dirt-beds in fig. 90.

In such an alternating series we generally find that there is a certain association between beds of finely divided and slowly accumulated matter, and a similar association of the coarser and more rapidly formed sandstones, pebble-beds, and conglomerates.

This association of beds is particularly well exemplified in the coal-measures, where a bed of coal almost invariably rests upon a layer of fine clay representing the argillaceous soil upon which the coal-plants grew. This layer is often termed the *underclay* in England, and the *coal-seat* in the south of Ireland. The general order of superposition is, (1) Sandstone; (2) Underclay; (3) Coal; (4) Shale. The roof, or argillaceous bed above the coal, is always more shaly than the underclay, and there is often shale below the latter separating it from the sandstone. This order of succession is illustrated by the following example taken from one of the memoirs of the Geological Survey:[1]—

No.	Beds.	Feet.
15.	Argillaceous shales	54
14.	Coal and shale	4
13.	Coal	1
12.	Underclay	4
11.	Argillaceous shale	4
10.	Sandstone	2
9.	Argillaceous shales	23
8.	Coal	9
7.	Underclay	3½
6.	Coal	0½
5.	Underclay	2
4.	Argillaceous shales	7
3.	Sandstone	1
2.	Argillaceous shale	2
1.	Sandstone	6

[1] "Mem. Geol. Survey," vol. i. p. 210 (Bristol coalfield).

Whether any particular bed is thick or thin depends upon the continuance or interruption of the conditions which led to its formation. For the formation of a great thickness of one kind of rock, it is probably necessary either that the sea in which it is being formed should be very deep, or that the area of deposition should be slowly and continuously subsiding, without causing any material alteration of the currents emanating from the sources of supply.

Thick accumulations of one particular kind of matter are by no means rare. Sandstones often occur in an uninterrupted succession of beds for many hundreds of feet, exhibiting every variety of texture, from coarse pebbly beds to layers of the finest possible grain, but without any appreciable admixture of argillaceous matter. Similarly, beds of clay or shale often form a continuous series of great thickness with hardly any intercalations of sandy or calcareous layers. The thickness of certain limestone formations is even greater, amounting, in some cases, to thousands of feet. Thus the chalk of England is in some places more than 1,000 feet thick, and the dolomite of South Tyrol has a thickness of from 3,000 to 5,000 feet.

Horizontal Extent and Thinning out of Beds.—The manner in which mechanical deposits are formed was described in Part I., Chap. XIV., and it was especially pointed out that such deposits generally preserved a regular order of succession from the coast outwards, the size of the transported particles decreasing with the distance from land, the finest muds being last deposited, till a limit is reached beyond which no such transported material is found, and its place is taken by sediment of organic origin.

It is clear, therefore, that where such a series of deposits as that represented in fig. 64 has been consolidated and elevated into land, a geologist engaged in tracing the beds across country in one direction, would find them rapidly changing in lithological character; the conglomerates will consist of smaller and smaller pebbles till they pass into coarse sandstones, the sandstones will become gradually of finer texture till, if he can trace them far enough, they will pass into beds of shale or clay. This change some-

times takes place rapidly, and within the compass of a single group of beds; in other cases, beds of sandstone alternate with the conglomerates, and as the latter gradually diminish in thickness, the former thicken and take their place. Similarly beds of shale may alternate and come in between beds of sandstone, and where the shales begin to thin out, beds of limestone may commence and finally take their place.

In one locality, therefore, we may find a series of limestones which may extend over a large area, but when traced in one direction will begin to be separated by little partings of shale. On following the group of limestones and shales still farther we might find that the shales became thicker and the limestones thinner as we proceeded. Finally some of the limestones might thin out and terminate altogether, while beds of sandstone commenced to

Fig. 91. Diagram of Lateral Change.

appear between the shales, until at length the series might consist almost entirely of shales and sandstones with only one or two beds of limestone to represent the purely calcareous group with which we commenced. Under these circumstances we should conclude that we had been approaching an ancient shore-line. Fig. 91 may serve as a representation of the way in which such lateral changes take place, the white bands being meant for limestones, the black for shales, and the dotted bands for sandstones: the figure, however, is a mere diagram, and would have to be drawn out to twenty or thirty times its length before it could be taken as a representation of natural deposits.

Every bed is in fact a great lenticular cake which thins out and terminates somewhere in every direction. As a general rule there is a definite relation between the extent and composition of beds, viz., that the finer the material

of which a bed is composed, the wider is its extent and the more equable its thickness. Individual beds of conglomerate and sandstone are generally thicker than single beds of shale or limestone, but they thin out much more rapidly, while beds of limestone and coal are often persistent over large areas, though they may be only a few feet in thickness.

Mr. Jukes observes that "the extent of single beds is most certainly ascertained in coal mining, in which the horizontal or lateral extension of beds is followed. Particular beds of coal, or of shale, or other rock having recognizable characters, are sometimes known to spread throughout a whole district. For instance, in South Staffordshire, a bed of smooth black shale, a little below the Thick or Ten-yard coal, is known as the 'Table batt.' It has a thickness of from two to four feet, and extends over all the greater portion of the South Staffordshire coal-field—places where it is known being ten or twelve miles apart from each other in different directions. Its original extension was probably much greater, since the beds now disappear in one direction by 'cropping out,' and are buried in others at too great a depth to be followed. Known beds of coal, with a particular designation, such as 'Heathen coal,' extend over still wider areas, and similar facts occur abundantly in most coal-fields. Mr. Hull states that one bed of coal called in part of the Lancashire coal-field the 'Arley Mine,' but known by other names in other parts, spreads over the greater part of the coal-field, which has an area of 192 square miles."[1]

On the other hand, beds of sandstone in the same coal districts frequently thicken or thin out very rapidly. An instance occurs near Wednesbury, in South Staffordshire, where a bed of sandstone known by the name of the "New Mine Rock" thickens out from 9 feet to 78 feet in the course of a few yards horizontal distance. In other parts of the district the sandstone varies from 60 to 15 feet, and in some places is entirely wanting.

A remarkable example of the persistence of the coal-seams for great distances and the impersistence of the

[1] "Manual of Geology," second edition, p. 185.

mechanical deposits is found in another part of the same coal-field. At Essington there is a certain group of "Coal-Measures," consisting of alternations of sandstones, shales, and coals, and attaining a thickness of between 300 and 400 feet. This group, when traced towards the south, thins so rapidly by the gradual dying away of the shales and sandstones, that in the space of five or six miles the different beds of coal come to rest directly one upon the other, and are continued as a compound seam of coal, 30 feet thick, with only a few shaly partings between the beds.[1]

Groups and Episodes.—From the explanations and examples given in the preceding pages it will be evident

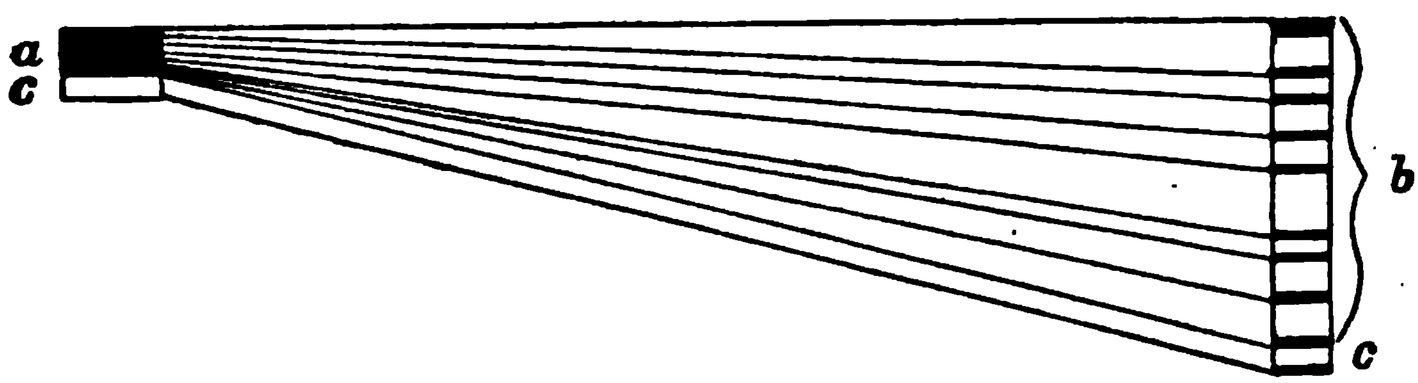

Fig. 92.

a, Thick coal. *b*, Thick coal group at Essington. *c*, Heathen coal.

that when geologists speak of a group of beds, they do not necessarily mean a set of beds of similar lithological composition, but a set of associated beds, connected together both vertically and horizontally, and deposited in contiguous areas during any given period of time. Such a series is found in the Carboniferous or Mountain limestone group. In Derbyshire this consists almost entirely of limestones, which succeed one another in massive beds for a thickness of more than 4,000 feet. When traced northwards, however, into Yorkshire, this great group is gradually replaced by a series of shales, limestones, and sandstones, which form several minor groups or divisions of the series.

[1] "Mem. Geol. Survey, S. Staffordshire Coalfield," second edition, p. 19.

Jukes long ago remarked[1] that "it occasionally happens that one large series of beds having a common character includes in some part of it a small, distinct set of beds with a peculiar character of their own," and he observed that some definite term was wanted to designate such an included set of beds. The name he then proposed has, however, been appropriated to express a different idea, and Prof. J. F. Blake has recently introduced the term *episode*,[2] which may be adopted as a convenient word for indicating the relation above mentioned.

An episode then may be defined as a small group or set of beds of limited extent possessing special characters which differ from those of the normal series within which it is included. It is, in fact, the lenticular development of a special set of beds formed under exceptional conditions, and therefore differing from those which were formed elsewhere at the same time.

Current Bedding. (1.) *Diagonal or Oblique Bedding.*—In fig. 82 the beds are represented as horizontal, each stratum resting evenly on that below; but stratification is not always so regular as this, because the surfaces on which beds are laid down are not always so even and horizontal. For instance, if a current is running over a surface which ends in a slope, the sand, which is being drifted along the bottom, will roll down the slope and remain undisturbed. Layer after layer of sand may thus be deposited in an inclined position according to the slope of the bank. Such a set of inclined strata is often formed where a river enters a lake, as described on p. 235, and is perhaps more frequent in delta deposits than any others, because river currents are, as a rule, more steady and continuous in one direction. An instructive instance has been described by Mr. Jukes in his memoir on the South Staffordshire coal-field. In this case observations in several quarries over an area of at least a quarter of a square mile showed that the beds of sandstone were inclined at an angle of 30°, and it was thought at first that this inclination was due to a subsequent tilting of the strata until another cutting was found, which showed that they rested on a horizontal bed

[1] "Manual of Geology," second edition, 1862, p. 201.
[2] "Brit. Assoc. Rep. (Sheffield)," 1879, p. 33.

of coal, and that it was merely a case of diagonal bedding. Similarly, near Corsham, in Wiltshire, a group of Oolitic limestones may be seen resting obliquely on other beds of shelly limestone, which are nearly horizontal.

(2.) *Curvilinear or Irregular Bedding.*—This structure is produced under similar circumstances to that just described, but should be distinguished from it, inasmuch as it is always a proof of frequent change in the velocity and direction of the currents by whose action the deposits were accumulated. *Diagonal bedding* is produced by the action of a steady current flowing continuously in one direction. *Curvilinear bedding* is caused by the meeting of currents which vary in force and direction from time to time. The term *False-bedding* has been applied to both structures, but is a misleading term, for both are truly bedded, though the inclination of the beds may be deceptive.

Sir Charles Lyell has described the appearance of a cutting through a sandbank formed near a junction of the rivers Arve and Rhone, where the conflicting currents had produced a series of inclined beds with curvilinear surface;[1] above these were more or less horizontal layers, surmounted by irregular alternations of sand and gravel in undulating curvilinear layers. Irregular bedding of this nature is the result of constantly shifting and conflicting currents, and is seldom exhibited by other deposits than those formed in shallow water, viz., sand and gravel, or sandstone and conglomerate, though it is not unfrequently developed in certain limestones which chiefly consist of the rolled and drifted débris of shells and corals, as, for instance, the great Oolite limestone of Bath and Minchinhampton, and the rock known as the Lincolnshire limestone.

Fig. 93 represents the arrangement of the beds in the face of a quarry at Minchinhampton, as sketched by Mr. Jukes.[2] Part only of the quarry face is shown in fig. 93, the top line being a marked plane of bedding; each bed is obliquely laminated, but the surfaces of the beds are all more or less curvilinear; it is evident also that none of these beds are complete, but are portions of so many banks

[1] See figure in Lyell's "Principles of Geology," ch. xix. fig. 44.
[2] See "Popular Physical Geology," Jukes, pl. 8.

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opposite direction to the inclination of the small stratulæ of which they are composed (see fig. 94). Each of these bands ends in a surface ridge or ripple.

Mr. Sorby states that in fine-grained sandstones which exhibit ripple-drift, the small stratulæ of sand are often separated by thin layers of argillaceous matter, the different bands being also separated by a similar deposit. He also finds a similar structure in beds of mica-schist, where the quartzose folia correspond to the sandy layers and the micaceous to the argillaceous layers, and showing that these schists were originally beds of shaley or flaggy sandstone.

An oscillating movement will also produce a ripple-marked surface, though not a regular succession of ripple-drift layers. This can be tested by oscillating a basin of water into which sand has been thrown. Waves produced by the wind produce an oscillating disturbance of the

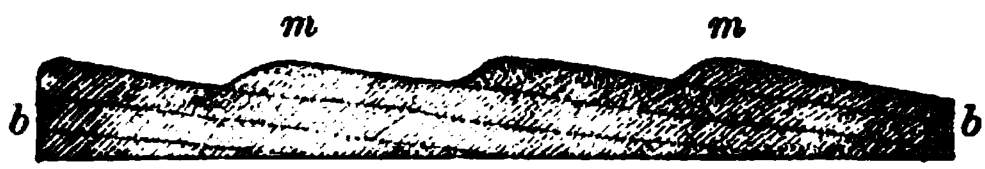

Fig. 94.

m, Ripple marks. *b*, Ripple-drift layers or laminæ.

material on the sea-floor, and as the influence of large waves extends to a considerable depth, ripple-marks may be produced in any depth at which this influence is appreciable. Tidal currents also disturb the bottom in fairly deep water under certain conditions (see *ante*, p. 182). Ripple-mark has in fact been observed beneath 50 to 60 feet of water.

Mr. Jukes observes that in places where the current is troubled, "a modification of these rippled surfaces is sometimes produced, the bed being irregularly mamillated on its surface, which is pretty equally, though irregularly, divided into small hollows and protuberances of a few inches diameter. This surface structure may be seen in process of production now on shores where spaces of sand are enclosed by rocks, so that as the tide falls it is made to run in different directions among the rock channels; but it would probably be caused at any depth at which a

current could be similarly troubled and confused. This might be called 'Dimpled current-mark.'"

It must be borne in mind that the rippled surfaces which are formed between tide-marks can seldom be preserved, because the incoming tide generally obliterates those previously formed. It is probable, therefore, that the ripple-marks preserved on ancient rock-surfaces have in most cases been formed beneath shallow water at a greater or less distance from low-tide level. A ripple-mark produced by the tidal current may be covered with the sediment which is deposited during the slack of the tide, and the new surface thus formed may be similarly rippled by the gentle movement of the return current, so that every successive layer of lamina will be ripple-marked. In fine-grained sandstones or sandy shales it is not unusual to find a succession of ripple-marked surfaces, one under the other, at distances of a few inches apart; and the direction of the ripples somewhat varies considerably on the different surfaces.

Mr. Sorby has shown that inferences may be drawn from the examination of these current-marks as to the velocity and direction of the currents which caused them, and that we may thus reason back to some conclusions regarding the physical geography of the district at the time they were formed.

Although, as above stated, ripple-marked beds are not usually such as were formed between tide-levels, yet surfaces are occasionally found which exhibit not only ripple-marks, but also sun-cracks, rain-prints, worm-tracks, and the footmarks of the various creatures which travelled over the moist, exposed surface of the bed. Such surfaces have doubtless been formed on flat shores, where large tracts were exposed between the lines reached by neap and spring tides, so that the surface beyond high water of neap tides, being exposed to the action of the sun, became cracked and hardened, and the next spring tide only spread over it another layer of sand or mud. Among lacustrine deposits they have doubtless been formed during dry seasons, when the lake waters shrank and large surfaces of the lake-floor were temporarily exposed.

CHAPTER VI.

CONSOLIDATION OF ROCKS.

IN the first part of this volume (Chapters XI. to XVI.) the manner in which deposits are now being formed in rivers, lakes, and seas has been explained; these being for the most part loose and unconsolidated sands, gravels, clays, and muds. In Part II., Chapter IV., the principal sedimentary rocks which are found in the earth's crust have been described, many of these being very hard and compact materials. It is natural that at this stage the student should ask how it is that deposits which were originally soft and incoherent, like most of those now being formed, have become so hard and consolidated as to be termed in ordinary language *rock* or *stone*. In the present chapter we shall endeavour to give some answer to this question.

The processes by which stratified rocks are consolidated may be mentioned under the following heads:—

1. Desiccation.
2. Pressure.
3. Infiltration.
4. Chemical change.
5. Heat.

1. **Desiccation.**—All stratified rocks which have been formed at the bottom of lakes and seas must of course be saturated with water for a long time after their deposition, as long, in fact, as the lake or sea remains above them. When at length earth-movements take place, and the subaqueous deposits are converted into land, they are partially drained of the included water, and their materials consequently settle down into a smaller space.

To take a simple instance, let us imagine a large and fairly deep lake which has during a long period received the sediment carried in by rivers and brooks, and in which several hundred feet of stratified deposits have been accumulated. Let us suppose that the country is then slowly elevated, and that the channel of the excurrent river is gradually deepened, so that the lake is eventually drained and its floor exposed. The main river which once flowed into the lake will then cut a course for itself through the lacustrine deposits, and the upper portion of these will be gradually dried or desiccated, the water in them being drawn out partly by evaporation from the surface, and partly by actual flow toward the river-channel, which will act as a natural drain.

The abstraction of water will cause a contraction of each layer or bed, as may be seen in the mud of a dried-up pond. Near the surface this contraction is mainly in lateral directions, generating cracks which are rifts at the surface, but get narrower and narrower as they extend downward into the mass; the reason of this being doubtless that the layers below contract less horizontally than they do vertically, owing to the pressure exercised by the weight of the layers above them. Partly then by contraction, and partly by the weight with which each successive stratum bears on that below it, the particles of every stratum are compressed into a smaller space, and are forced to cohere more closely together. This is generally the first stage in the process of consolidation.

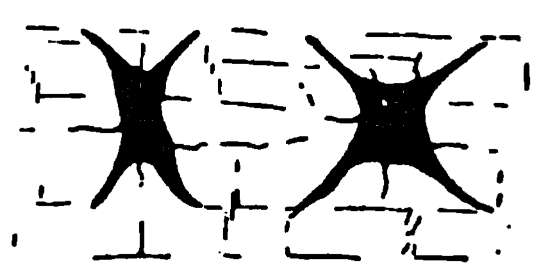

Fig. 95.

An excellent illustration of the amount of contraction and compression which a calcareous mud often undergoes in the process of conversion into a limestone is afforded by a bed in the Lower Purbeck group of the Vale of Wardour. This is a pale yellowish-grey earthy limestone, containing many small shells of species that can live in brackish water, and exhibiting many curious cavities of the shapes shown in fig. 95, some of them empty, and some of them filled with ferruginous matter. These are spaces left by

the solution of cubical crystals of common salt; they show that when the deposits were raised into dry land, the salt was dissolved and removed, and that the material contracted by desiccation under the pressure of the overlying strata (some 200 feet) to such an extent, that the walls of the cavities were forced inwards. The squeezed-up shapes of the cavities show that this must have taken place while the mass was soft and plastic, before it set into the hard limestone it now is. In some of them the walls have "caved in" equally, but in many two sides have given more than the rest, while sometimes they are all so bent in that little space remains between them.

2. **Pressure.**—In the case taken above we have supposed the thickness of the lacustrine deposits to be only a few hundred feet, but the geologist often finds marine strata which form a continuous series for several thousand feet, and it is obvious that the lower parts of such masses must have been subjected to considerable pressure from the mere weight of the overlying beds. Further, where such thick formations rest on still older rocks, these latter must have borne the whole weight of the newer series. For example, the thickness of the Carboniferous system in Lancashire is estimated at about 20,000 feet, and the whole of this great pile of sediment was accumulated in horizontal layers in a subsiding area. When complete this great formation must have borne with its whole weight upon the underlying rocks, and the vertical pressure thus exercised must have been very great.

Again, in subsequent chapters proofs will be given that, during the movements which have taken place in the crust of the earth, stresses have been set up which have subjected certain regions to enormous lateral pressures. It will be shown too, that such compression has not only consolidated the rocks by forcing their component particles into closer collocation, but has actually caused these particles to move and rearrange themselves in accordance with the direction of the stress, thus developing new and peculiar structures in the rocks exposed to its influence.

The results of simple pressure are illustrated by several processes in arts and manufactures; thus, the black lead of pencils is formed by compressing the powdered dust of

graphite, and tiles or tesseræ have been made by the compression of porcelain-earth.

More astonishing, however, is the power of suddenly-applied pressure to consolidate instantaneously such a material as loose sand. This is demonstrated by arrangements made for trying the strength of gunpowder. A cannon-ball is fired from a gun charged with the powder to be tested at a mortar in which leathern bags filled with sand have been placed to receive it. The sand is often compressed by the percussion of the ball into a mass of sandstone sufficiently firm to remain solid and to bear handling.

Many sandstones have been compacted by simple pressure, their component particles having been so closely packed by this process that they adhere to and support one another; a slight scattering of mica flakes among the sand greatly facilitates its acquisition of coherency. Soft sandstone which just holds together in this way is sometimes called "sand-rock," and if it is firm enough to be cut into blocks these sometimes show a certain amount of flexibility; for if a long block of the stone is supported at both ends it will curve and sag down in the centre. Such is the Itacolumite or Flexible Sandstone of India and Brazil.

There is no more striking proof of the enormous pressure to which some rocks have been subjected than that furnished by certain conglomerates, the pebbles in which have indented each other. In these beds, pebbles of the hardest rocks, such as Quartzite, are dented and squeezed by compressive contact with one another, as if they had been lumps of dough or putty manipulated by human fingers. Some pebbles may be found among them which have been split into several pieces, but held together and subsequently recemented by infiltrated silica or calcite.

3. **Infiltration.**—In many cases the consolidation of a rock is assisted or completed by the infiltration of some mineral cement. It has been stated that rain-water percolating downward through the soil and underlying rocks dissolves and holds in solution many of the mineral substances which it meets with (see p. 84), and that under certain circumstances these substances may be redeposited in the cracks and interstices of the rocks at a greater or

less depth from the surface. This process of infiltration may go on till all the interspaces between the original particles of a rock are filled up with crystalline or colloid matter, and the whole mass is bound into a hard and compact mass. This cement may be ferruginous, calcareous, or siliceous.

In coloured sandstones the grains are generally found to be coated with a film of peroxide of iron, which has been formed in the manner explained on p. 86; this gives characteristic red, brown, and yellow tints, according to the thickness of the film, and it unites the grains together, though it seldom completely fills the interstices between them.

The cementing power of oxidized iron is seen when any mass of the metal is allowed to rust in water; a few horse-shoes or a bag of nails will suffice to agglutinate a considerable mass of material. Dr. Mantell has described a ferruginous conglomerate dredged up off Hastings, consisting of glass beads, knives, and sand, the two former being derived from a Dutch vessel which was stranded there in the last century.

Calcareous infiltrations are also very frequent. Calcareous sandstones have been described on p. 358, and the manner in which the calcite crystals sometimes embody the sand-grains was there noticed. A curious modification of this structure occurs in the sands of Fontainebleau, from which free and perfect rhomboids, consisting of fine sand embedded in calcite, have been obtained. Many limestones have been consolidated by the subsequent infiltration of calcite (see p. 362), which has gathered the fine paste or matrix of the rock into its crystalline structure, and has produced a more or less crystalline limestone. At the same time, all the organic remains which consisted of aragonite have been dissolved and replaced by crystalline calcite. When a slice of such rock is examined under the microscope, the calcitic matrix is seen to be opaque or cloudy with the included calcareous mud, while all the spaces which were not originally filled with this mud, and all the replaced aragonite structures, appear in clear transparent calcite.

Siliceous infiltrations have also been mentioned (p. 359);

the Hertfordshire puddingstone is an excellent instance of such consolidation, for the pebbles and sand-grains of which it mainly consists are so firmly glued together by the chalcedonic cement that a fracture breaks across them, even dividing the sand-grains, which appear as clear crystal-like specks on the fractured surface. The "grey wethers" and "sarsen stones," so common on the chalk downs of Berks and Wilts, are relics of similarly agglutinated sandstones. A fine-grained sand embodied in a chalcedonic cement is often called a *chert;* thus Mr. A. Strahan describes[1] a mass of "chert" in Flintshire over 300 feet thick, which passes laterally into a granular sandstone with a siliceous cement, and ultimately into a conglomerate or puddingstone.

4. **Chemical Change.**—In some cases the whole material of a rock is altered from its original condition into a different chemical substance, and this is sometimes a cause of consolidation. The conversion of woody and peaty matter into coal comes under this head, for though, no doubt, it is partly due to simple pressure, and the pressure may have assisted the chemical action, still the gradual elimination of oxygen, and the condensation of the solid carbon, must have tended to the consolidation of the mass.

The alteration of limestone into dolomite by the filtration of water containing magnesic chloride and sulphate, resulting in the replacement of part of the lime by magnesia, which combines with the remaining calcic carbonate to form dolomite, is another instance of a chemical change which causes consolidation by the consequent contraction and crystallization of the rock.

5. **Heat** assists the processes of consolidation, which have already been mentioned, and it has also a special action of its own.

Sedimentary rocks may have come within the influence of heat in three ways. They may have been buried so deeply by other deposits that for a time they occupied a low position in the earth's crust, where the temperature was much greater than near the surface. As the tempera-

[1] "Mem. Geol. Survey," Explanation of Sheet 79, N.W.

ture at the bottom of Rose Bridge Colliery (2,450 feet) is 94° F. (see p. 12), that at the bottom of the Sperenberg boring (4,040 feet) is 120°, and that of the water from a boring near Pesth (about 3,000 feet deep) is 160°, it is evident that the water in rocks which lie at 4,000 to 5,000 feet below the surface must everywhere be very hot, and that at a depth of between 7,000 and 8,000 feet it must in many places be as hot as boiling water is at the surface. Now we have already stated that strata which were formed at the surface have frequently been buried to a much greater depth than 8,000 feet.

In volcanic districts the rocks are heated by the influence of the rising lava, and may acquire a high temperature at a comparatively small depth from the surface. In every district, therefore, where volcanic rocks occur, we may expect to find evidence of the effects of heat on stratified rocks.

Lastly, heat may be developed locally by mechanical force, such as that of lateral pressure, which has sometimes been carried to the extent of crushing the rocks.

The hardening effect of dry heat is well known, and any rock exposed to the contact of liquid lava must be baked and indurated; the phenomena of such contact-metamorphism will be described in a future chapter.

The passage of heated water through stratified rocks, whether in ascending or descending currents, must have a powerful effect in dissolving and rearranging the constituents of the rocks, and its continued action may lead to a high degree of alteration and consolidation.

It will suffice in this connection to indicate some of the changes which can be produced by this agency:—Hot water attacks and dissolves mineral matter much more readily than cold water, so that, as we often see in hot springs and geysers, pure silica can be held in solution by water which is below the boiling point, and is deposited as the water cools. This process must frequently go on beneath the surface, and the silica must be deposited in the form of a siliceous cement in those portions of the rocks where it loses heat.

The changes which can be effected without a very high temperature are illustrated by the formation of many

minerals, including some hydrated silicates or *zeolites*, in the interstices of the bricks of a Roman bath at Plombiéres in France by the waters of a warm spring. The minerals were formed by the action of the water on the materials of the bricks, and its temperature is only 122° F., or about that of the water at Bath in England.[1]

Not only can moderately warm water effect such results, but the very solutions which it takes up at ordinary temperatures increase its capacity for dissolving other minerals, and if such water percolates downward till it acquires a high temperature, none of the ordinary constituents of rocks could withstand its potency. Dr. Sterry Hunt has shown that water containing alkaline carbonates will, at a temperature of not more than 212° F., rapidly dissolve silica, and generate various silicates. Again, it was proved by Daubrée that in the presence of dissolved alkaline silicates at a temperature above 700° F., various siliceous minerals, such as quartz, felspar, augite, could be formed and crystallized out.[2]

CONCRETIONS.

It will be convenient in this connection to give some account of the different kinds of nodules which occur so frequently in stratified rocks, and are known by the name of *concretions*. As this term is often used in a loose and ill-defined sense, we shall here restrict it to such lumps or nodules of mineral matter as have a different chemical composition from that of the rock-material which encloses them; those nodules which are merely spheroidal lumps of the rock-mass, developed during the process of consolidation, are therefore excluded from the present category. These latter we regard as structural developments produced by physical forces, while the former have been produced by the operation of chemical forces. This chemical action may have operated during the deposition of the bed in which the concretions are found, or during its consolidation, and it is a mistake to suppose that they

[1] "Quart. Journ. Geol. Soc.," 1878, p. 73.
[2] "Bull. Soc. Geol. de France," tom. xv. p. 103.

have been entirely formed by a process of segregation after the consolidation of the surrounding material.

In most cases it is evident that the concretions must have been formed while the enclosing deposit was sufficiently fresh and plastic to allow of free molecular movement within its mass; it has also been proved that many such nodules owe their origin to the decomposition of organic matter, and in these cases the concretions must have begun to form while the rock-mass was still permeated with the water in which it was deposited, and before it had been covered up by any very great thickness of subsequently-deposited material. Organic bodies decomposing on the muddy bottom of a lake or sea evolve carbonic acid, carbonate of ammonia, and other chemical substances, which react on the substances dissolved in the water, and cause the precipitation of various mineral compounds. Other causes may assist in the production of concretionary nodules, and the whole subject requires farther study and investigation. We now proceed to notice the different kinds of concretions which occur among aqueous rocks.

In Sandstones concretionary nodules are generally either calcareous or ferruginous. In some sandstones large spheroidal masses of calcareous stone occur, which appear to be portions of the sandstone bound together by carbonate of lime. These are called *doggers* in the north of England; they often abound in fossil remains, while the loose sand outside does not contain any. Other sandstones contain concretions of iron pyrites, varying in size from mere grains up to masses as large as the fist.

In Clays and Marls. There are few large deposits of clay which do not contain concretions of some kind.

Septaria consist chiefly of carbonate of lime with some carbonate of iron, and occur in many clays, forming large nodules which sometimes attain a diameter of 2 to 3 feet, or even more. In true septaria the interior is split up by numerous cracks, which are generally filled with calcite, forming divisions or *septa*, but similar concretions which are entirely solid often occur in clays.

Cornstones.—Beds of cornstone have been mentioned on p. 358, but these often pass into layers of separate concretions, which may be called cornstone nodules.

Clay-ironstone nodules are of similar construction, but consist chiefly of carbonate of iron mixed with more or less clay and carbonate of lime. When broken open the smaller nodules frequently disclose a fossil shell or leaf which has evidently formed the nucleus round which the ferruginous matter has accumulated; they often have a septarian structure.

Phosphatic nodules occur in clays and calcareous shales, and are composed of phosphate and carbonate of lime in variable proportion. Those from the Gault and Cambridge greensand contain from 56 to 60 per cent. of the phosphate, with 10 to 12 per cent. of the carbonate, but the Suffolk nodules (derived from the London Clay) are less rich in phosphate with more carbonate of lime, and a considerable amount of iron. They are commonly but erroneously called *Coprolites.*

Marcasite nodules, or balls consisting of that variety of iron pyrites called Marcasite, are also abundant in many clays, especially where organic remains are abundant, and frequently enclose some fossil shell or plant.

In Limestones the concretions are either siliceous, ferruginous, or phosphatic.

Flint and Chert are well-known substances, the composition of which has already been described; both occur as nodules of irregular, and often eccentric form.

The origin of the flints in the chalk, and of the chert nodules in other limestones, was long a matter of doubt, but recent researches have gone far to explain the process. Dr. Bowerbank was the first to suggest that sponges had been much concerned in the formation of flints; and recently Professor W. J. Sollas has made this more certain, and has given the following explanation of their origin. He thinks that the siliceous spicules of numerous sponges gradually accumulating in the chalk ooze, and in presence of sea-water under great pressure, would enter into solution as organic silica; that where the sponge growth was very thick, it contributed so much silica to this solution as to render it concentrated enough for the deposition of mineral silica, which replaced a certain amount of the calcareous ooze. The calcareous material thus became siliceous chalk, and ultimately a further deposition of silica

replacing the remainder of the calcic carbonate converted the siliceous chalk into the dark flint as we now find it.

This view receives confirmation from the discovery of siliceous chalk with imperfectly formed flints in Wiltshire.[1]

Marcasite nodules also occur in some limestones, generally in the form of rounded lumps or balls, which have a radiated crystalline structure internally. Many of those in the Lower Chalk of Folkestone are irregular in form, and seem to have been formed by the pyritization of the siliceous sponges known as Ventriculites. The connection of iron-pyrites with decaying organic matter is so persistent that we may safely attribute all such pyritous nodules to the decomposition of organic bodies.

Phosphatic nodules are occasionally found in shaly limestones, as in the Bala limestone of North Wales. Nodules containing more or less phosphate of lime also occur at several horizons in the chalk; they seem to be generally lumps of chalky mud which have been derived from an older deposit of Chalk, and partially consolidated before being washed into the bed where they are now found; they are generally coated with a green chloritic or glauconite substance. Those in the Chalk-rock contain 5 or 6 per cent. of the phosphate, those in the Lower Chalk 15 to 20 per cent, and those from the Chloritic Marl from 35 to 50 per cent.

[1] See "Quart. Journ. Geol. Soc.," vol. xlv. p. 410.

CHAPTER VII.

JOINTS.

IN Chapter V. stratified rocks were described as consisting of layers or strata separated by planes of division which result from the manner in which the strata were accumulated; but all rocks, whether stratified or unstratified, exhibit other features which have been produced during the process of their consolidation.

There are few exposures of stratified rocks which do not exhibit certain other planes of division besides those of lamination or stratification. These are the *joints*, or long cracks which cut across the bedding planes and separate each bed into blocks of various shapes. It is obvious that in stratified rocks there must be at least two sets of joint planes besides the planes of stratification, in order to cut up the beds into blocks. In igneous or unstratified rocks it is equally obvious that in order to form squarish blocks we must have at least three sets of joints crossing each other, each set more or less nearly at right angles to the other two.

Origin of Joint Structures.—Everyone who has examined the muddy bottom of a dried-up pond or lake is aware that, as the water evaporates and the mud dries, long and deep cracks are formed which traverse the dry mud or clay in various directions, and cut it into polygonal blocks. The width and depth of these cracks depend partly upon the extent and thickness of the mud.

In the same way molten rock shrinks and cracks in cooling. Attempts have been made to utilize the slags from iron-furnaces by running them into moulds, but the

quadrangular blocks so obtained proved to be useless for building purposes because they cracked and crumbled into small cuboidal fragments in consequence of the numerous joints developed during the process of cooling and solidification. Differences in the texture of rocks will naturally cause differences in their manner of cracking, and so different forms of jointing will be produced. The number of joint-planes will also partly depend upon the thickness of the bed or mass. Some beds will shrink more than others, and some masses of igneous rock must have cooled more rapidly than others.

Mr. Jukes has remarked that it does not follow that all the joints in any mass of rock should be formed at any one time. "The consolidation of the mass may take place slowly and gradually, and successive sets of joints be produced in it at different times during that process. A rock, moreover, may be, at some subsequent period, placed under circumstances calculated to produce a greater degree of consolidation, and a fresh set of joints may be produced in it from that cause.

"The small or short joints confined to individual beds of stratified rocks may have been those first formed on the original consolidation of the one bed before the next was deposited on it, those joints being then, perhaps, quite imperceptible divisional planes with no interspace between the blocks. Whole sets of beds may have subsequently been subject to one, two, or more actions of consolidation, which may have produced larger joints traversing the whole mass. Still more extensive joints may have been formed subsequently by the mechanical agency of the upheaving forces acting on the crust of the globe." [1]

M. Daubrée has lately obtained some curious results by submitting plates of various substances to the effects of torsion, and finding that he could by this means produce sets of cross fractures similar to ordinary joints, he boldly ascribes all joints to the action of force similarly applied.[2] Mr. J. G. Goodchild,[3] however, has pointed out that joints are of various kinds, and are not likely to have all been

[1] Jukes' "Manual of Geology," second edition, p. 218.
[2] "Geologie Experimental," vol. i. p. 300 *et seq.*
[3] "Geol. Mag.," Dec. 2, vol. x. p. 397.

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lines of lamination, and the surfaces thus exposed along the tops and bottoms of the lumps are generally dull and earthy, and readily soil the fingers. At right angles to these surfaces others may be observed, which are generally bright and shining, and if the coal be freshly broken, these surfaces will soil the fingers much less than those on the top or bottom of the lump. He will see that there is one set of smooth, vertical surfaces (or joint planes), along which there occur the cleanest, largest, and most even sides to the block, the vertical surfaces at right angles to that set being shorter, rougher, and more irregular. The first large, smooth, vertical surfaces are known by the name of *the face, the slyne*, or *the cleat*, of the coal in different districts,—the more interrupted set being spoken of sometimes as the *end* of the coal."[1]

In a series of stratified rocks each bed generally has its own system of joints, which are close and regular and do not penetrate the beds above and below. There are always others, however, which are common to several successive beds, and seem to have been formed simultaneously, though they often change their direction a little in passing from one bed to another. Lastly, there are some still larger and longer planes of division, which cut through many successive beds, and maintain the same direction both vertically and laterally for very long distances; these are called the *master-joints*. The master-joints sometimes form a more conspicuous feature in the rock than the planes of stratification do, and are occasionally found to cut across whole mountains in regular parallel lines. These large joints are often open fissures with a space of an inch or more between the walls, and in limestones this space has frequently been widened still more by the action of percolating water. Such joints are always well developed in limestone districts (see the Frontispiece, and also p. 86, and fig. 28).

Surface Exhibition of Joints.—Although the general characters and vertical course of joints may be readily observed in almost any stone-quarry, there are not such frequent opportunities of studying their horizontal exten-

[1] Jukes' "Manual of Geology," second edition, p. 212

sion or surface exhibition over large areas. Mr. Jukes found that the newly-formed beds of stone which occur on some of the coral islands off North-east Australia were already divided by a system of joint-planes. He says:—"I often observed several beds of stone resting on each other, each more than a foot thick, inclined at an angle of 8° or 10°; that is to say, at the same angle as the slope of the beach or bank of sand on which they rested. They had, to all appearance, been consolidated in this position. The joints which traversed them, although often uneven and jagged, ran in straight parallel lines over spaces sometimes of 200 yards, or as far as they could be seen, their planes being generally at right angles to those of the beds, one set of joints running along the greatest linear extension of the mass (*strike-joints*), and the other set directly across the former, and in the same direction as the inclination of the mass (*dip-joints*). The directions of these two sets of joints seemed to depend in these cases on the directions of the principal bounding surfaces or edges of the mass."[1]

The surface exposure of a hard rock like limestone is sometimes so bare of soil as to present an excellent field for observing the horizontal extension of joint-lines, and perhaps no district offers better facilities for such a study than the barony of Burren in county Clare, Ireland. Hills of limestone here rise more than 1,000 feet above the sea, the stratification being almost horizontal, the hill summits and the terraces that sweep round their sides showing broad floors of bare rock over the whole country. The joints, which are very numerous and very regular, have been widened by the rain, so as to form superficial crevices, sometimes several inches in width and several feet in depth. The floors of limestone are cut by them into a number of separate blocks of quadrangular and triangular forms. The late Mr. F. J. Foot, of the Geological Survey, who examined this district, has given a detailed account of these joints in the explanations of the maps 114, 122, and 123, of the Geological Survey of Ireland. He found that there were three distinct sets of joints, besides other small

[1] Jukes' "Manual of Geology," second edition, p. 217.

and irregular cracks. Two of these sets of joint-planes were nearly parallel to one another and ran nearly north and south, one a little E. of N., the other a little W. of N., so as to produce large wedge-shaped blocks several feet long, ending in angles sometimes as sharp as 5°. These master-joints were crossed by others running nearly east and west, not in straight, but in gently curved serpentine lines. The straight north and south joints sometimes stopped suddenly at one of these cross joints, and it was observable that the neighbourhood of one joint-plane, or the space between two adjoining planes, exhibited a number of closely adjacent parallel joints, not more than an inch or so apart, which split the beds across into vertical slabs (see p. 86, and fig. 22.)

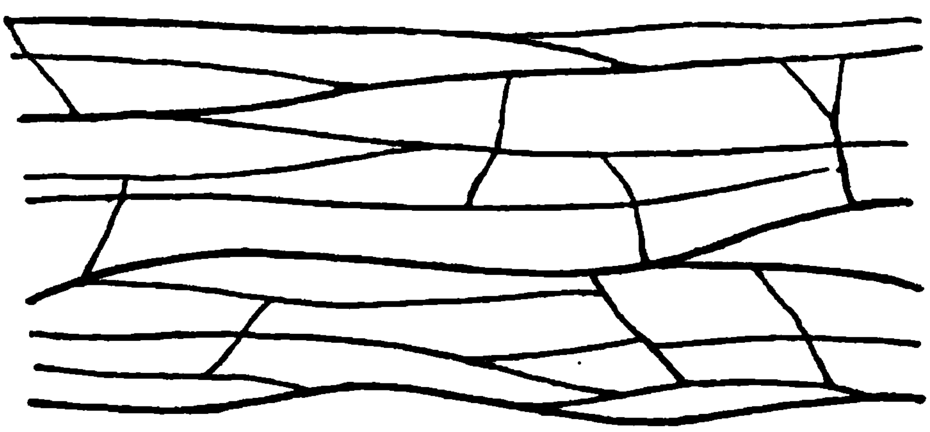

Fig. 97. Horizontal Jointing in Chalk.
Scale about 12 feet to an inch.

The disposition of joints may also be studied on rocky shores, where the surface of one hard bed is sometimes bared for a considerable extent between tide-marks.

Horizontal Jointing.—Besides the vertical joints which are so conspicuous in all stratified rocks, a series of horizontal joints is frequently developed. In many cases it is difficult to distinguish these from the planes of bedding, and probably they are most strongly developed in massive homogeneous rocks which do not exhibit frequent or distinct planes of stratification. They are specially noticeable in the more compact and marly varieties of chalk where the usual planes of bedding are entirely obscured or replaced by a set of irregular and curvilinear joint-planes, which bear some resemblance to those of actual curvilinear bedding produced by current action (see

p. 386). Fig. 97 is taken from a sketch in a chalk quarry near Cambridge, where this structure is well exhibited.

A somewhat similar kind of jointing has sometimes been produced in igneous rocks, and has been called "*Curvitabular structure*" by Professor Bonney, who has described an instance in a part of the basalt of the Plateau de la Prudelle, Auvergne. "The mass," he says, "is traversed by a series of more or less horizontal curving joints, with their convexities upward; so that the whole is divided into a series of plano-convex, meniscoid, or concavo-convex blocks, in length perhaps about 2 to 4 feet, and in thickness from 4 to 12 inches. This structure continues with but slight indications of any tendency to vertical master-joints for some 35 feet."[1]

Granite and other igneous rocks often exhibit a much

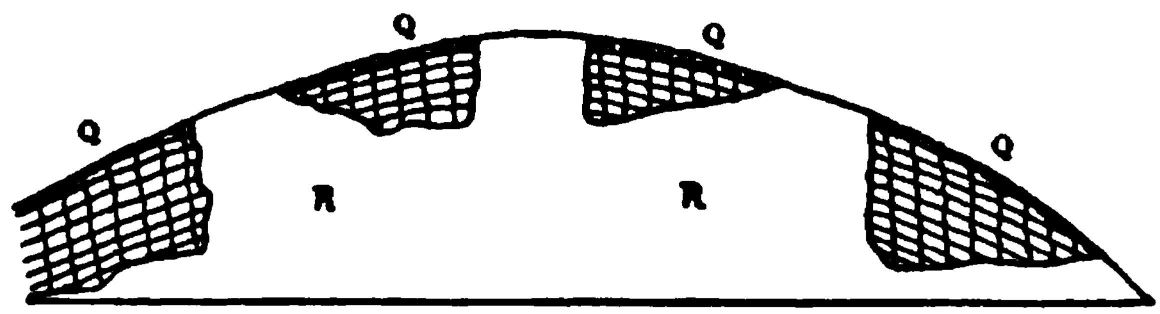

Fig. 98. Joints in Granite near Penrhyn.
Q Q, Open quarries. R R, Unquarried rock.

more regular series of horizontal joints, which together with the vertical joints, split up the mass into a succession of tabular blocks. Such joints are especially well developed in the granites of Cornwall, where they are called *bedding-joints* by the miners. It is a noteworthy fact that these bedding-joints are not truly horizontal, but run in broad curves, which closely correspond with the curvatures of the surface of the ground. The quarries are generally opened on the slopes or summits of hills, and it is stated by Mr. G. F. Harris that in every case the run of these joints approximately follows the curve of the hill.[2] Fig. 98 is reproduced from one given by him to illustrate this, and shows the directions of the two main sets of joints in the

[1] "Quart. Journ. Geol. Soc.," vol. xxxii. p. 146.
[2] "Granites and Granite Industries," 1889, p. 104.

quarries on Carnsew Hill, near Penrhyn. The "bedding-joints" are crossed by nearly vertical master-joints, and again at nearly right angles by another set of steeply inclined joints, so that the rock-mass breaks into nearly cubical blocks. When these blocks are exposed to atmospheric disintegration the corners and edges crumble away, the joints are widened, and the result is a pile of separate blocks, resting loosely one on the other. In granite districts these piles are called *torrs* or *cheese wrings;* the logging-stones or rocking-stones are also due to the development of a similar structure (see p. 100).

As regards the origin of this horizontal jointing, the tabular structure in granite and other igneous rocks may, in some cases, be due to the tensions caused by alternate expansion and contraction under diurnal variations of temperature; for rapid contraction at night after expansion by the sun's heat during the day is likely to produce normal as well as horizontal strains in the rock-mass.

The curvilinear planes in chalk may perhaps be due to an analogous process, for chalk must be particularly liable to such changes of dimension in consequence of its capacity for holding water. The drawing up and evaporation of this water by the sun during dry weather must cause rapid desiccation and contraction. Near the surface the chalk is broken up into small tabular fragments, but lower down the result may be different. The strains in a horizontal direction will be relieved by vertical joints, but there must also be strains in a vertical direction, and these can only be relieved by cracks which are more or less horizontal or parallel to the surface of the ground. Once formed they would always remain as divisional planes, and the subsequent passage of water along them would only tend to keep them open.

Prismatic Jointing.—Unstratified rocks cannot fall into cubical blocks unless the vertical joints are crossed by another set of horizontal joints. Without these it is clear that the vertical joints will split the mass into long columns or prisms, the shape of which will depend on the number of intersecting joint-planes. This form of jointing has been termed *prismatic,* as tending to the formation of prisms, and it is only from rocks which are thus prismati-

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Mr. Fisher has kindly supplied me with another demonstration of this, which is perhaps more easily understood. In a homogeneous rock like basalt the contractile force seems to be exerted so evenly throughout the mass, that we may assume it to tend toward a set of equidistant points. Such equidistant points must be at the corners of equilateral triangles. Let A B C be such points, and suppose the rock-substance to be drawing away from each point equally, this substance will part at points which are midway between A and B, A and C, B and C. The cracks so generated will run in straight lines till they meet. Let D be another point equidistant from B and C, and suppose similar cracks to be formed between B and D and between C and D, then it is easy to see that, when a complete system of such cracks is produced, all extending till they meet one another, the spaces enclosed by them will be hexagons. The cracks thus commenced will strike down into the cooling mass, and will result in the formation of regular hexagonal columns.

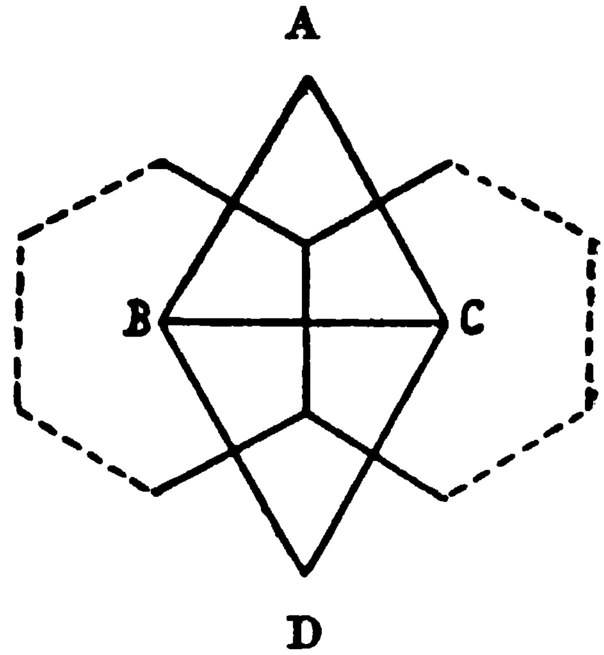

Fig. 103.

The columns are straight and regular in proportion as the cooling proceeded uniformly from a plane surface; but if the cooling surface was convex, the columns must strike inwards towards a centre; while, if it was concave, they would radiate outwards in different directions. Again, the opening of fissures within the mass would provide other cooling surfaces from which independent sets of columns would be started. Thus it frequently happens that in the upper part of extruded bosses or streams of lava, the columns are inclined or curved in various directions, while the lower part of the same mass is regularly divided into straight and vertical pillars; the two portions being separated by a more or less horizontal plane of tension.

Again, in dykes of igneous rock the columns are always at right angles to the bounding walls, and have evidently started from these surfaces where the cooling and consequent consolidation would necessarily commence, as in fig. 101. Moreover, it often happens that the columns are not continuous across the dyke, but are separated into two sets by a medial plane. In this case it is clear that the columns originating on either side of the dyke struck inwards, and met along the medial line, but the axes of the columns not being in the same line the two sets of columns could not coalesce into uniform bars.

Articulated Columns and Spheroidal Structure.—Columnar lavas sometimes exhibit a still more curious and complicated structure, occasioned by transverse articulations or planes of division which traverse the columns at nearly equal distances so as to split them up into a series of separate hexagonal blocks. The surfaces of these transverse cracks are sometimes flat, but more often curved, and sometimes they fit into one another with a kind of ball-and-socket arrangement. Professor Bonney has shown that all these jointed, tabular, and cup-and-ball structures are referable to the same cause, viz., contraction while cooling; and in one case he has noted a sort of transition from a regular jointed column to a broad prism with slightly curved walls and a kind of curvitabular cross-jointing (see fig. 104).

In other cases a spheroidal structure has been developed, the whole mass of rock separating into large balls which exfoliate under the action of the weather into regular concentric layers or coats, like those of a large onion. It was formerly supposed that this spheroidal structure was simply a mode of weathering. It is true that cuboidal blocks of rock, such as those of granite, have a tendency to weather into rough spheroids, and further decomposition might sometimes produce a kind of concentric exfoliation; but this is not sufficient to explain all the instances of spheroidal structure that have been observed.

In the first place, a similar structure is occasionally developed in rocks which are not jointed so as to split into cuboidal blocks; an excellent example of this in bedded shale has been described and figured by Mr.

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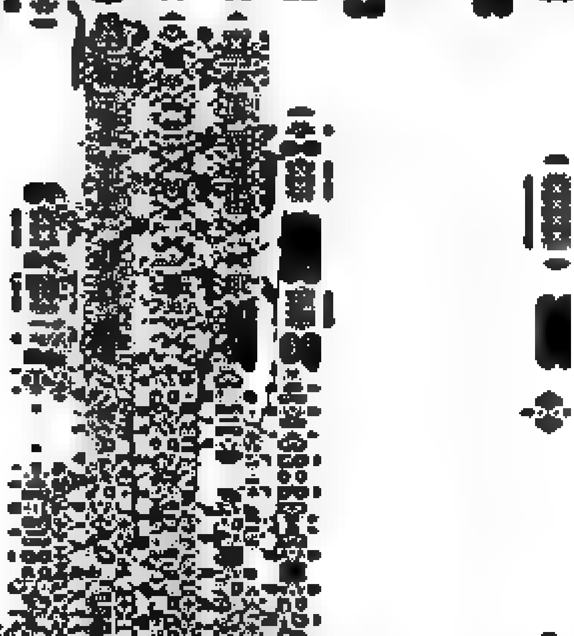

Fig. 181. Spheroids in Co-
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wards to the less solidified part, and the spheroids, at the same time, formed within this more plastic part of the column, the two surfaces of division running together at last so as to complete the separation.

The precise manner in which these spheroids are developed is not very easy of explanation, but if it be assumed that contraction is taking place uniformly throughout the mass of the cooling material, then spheres may be formed in this mass on the same principle by which hexagons are formed on a plane surface; a sphere being the solid of least superficies for a given volume, and being the figure where the contractile force acts everywhere perpendicularly to the circumference. If the joints simultaneously produced are few and far apart, the spheres will remain spheroidal; but if hexagonal columns are being produced at the same time, the spheroids necessarily come to have a hexagonal circumference, and are regularly superimposed one on another. Whether the top and bottom of each block is flat, convex, or concave, depends probably on differences in the strains or tensions within the mass.

Art of Quarrying.—Without natural joints the quarrying of stratified rocks would be very difficult, and that of igneous rocks would be almost impossible, for each block would have to be cut out on every side from the rest of the solid mass. The whole art of quarrying consists in taking advantage of the natural division of the rock by the planes of jointing and bedding, where the latter exist. The shape of the quarry will therefore depend on the direction of the master-joints which traverse the stone. One set of these joints will form what is called the *face* or *back* of the quarry or the boundary wall towards which the men are at any time working; while the other set of joints, at right angles to these, are the planes along which they work; these are called the *ends*, or sometimes the *cutters* of the stone.

In mining operations where adits and galleries are driven into the rock, it is still more necessary to observe the direction of the joint-planes, for by these natural lines of division will the direction of the passages be regulated. This is particularly the case in coal-mining, for, as already stated, beds of coal exhibit not only the ordinary system of distant

joint-planes, but also a system of minor joints which retain their parallelism over very large areas; the main galleries of a coal-mine, therefore, are always driven along the face of the coal, while the cross galleries run along the end of the coal. To attempt to cut galleries across that direction in which the coal will naturally split into blocks would obviously be a much more difficult and expensive task than to take advantage of this structure.

CHAPTER VIII.

INCLINATION AND FLEXURE OF BEDS.

WE could not continue our observations upon stratified rocks very long without perceiving that their beds are not always horizontal, but are, on the contrary, generally inclined to the horizon at a greater or less angle.

We have already seen that in certain cases beds of stratified rock may have been originally deposited on a considerable slope. Such beds, however, can only be of very limited extent, and we can hardly imagine a succession of parallel beds to have been deposited with exactly the same slope; neither is it possible for materials finer than coarse sand to rest on a slope having a greater inclination than 35°. Whenever, then, we find a set of inclined beds maintaining an equal thickness and approximate parallelism over a wide extent of ground, we may feel quite sure that when first formed those beds must have been practically horizontal, and that their present inclination is the result of subsequent movement. They must have been tilted, either by being lifted up at one end or depressed at the other, and in many cases the beds have been subjected to such powerful and long-continued movements that they are tilted up at very high angles, and in some cases are set on edge in an absolutely vertical position.

Dip and Strike.—The inclination thus given to beds of rock is called their *dip;* its amount is expressed by the number of degrees contained in the angle between the plane of the beds and the plane of the horizon, and the

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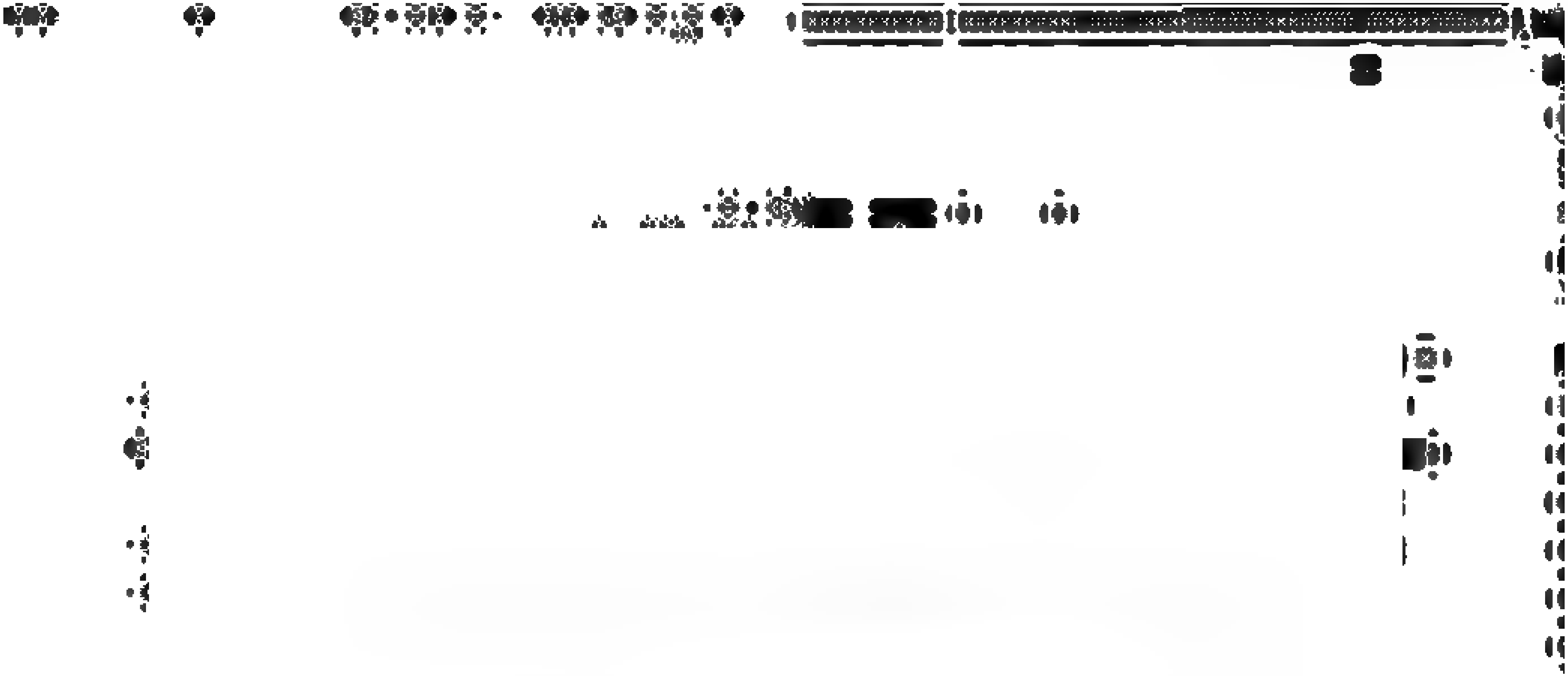
Sir Charles Lyell compares dip and strike to a row of houses running east and west, "the long ridge of the roof representing the strike of the stratum of slates, which dip on one side to the north, and on the other to the south." The line of strike, however, is not always a straight line, because any change in the direction of the dip will produce a corresponding change in the direction of the strike.

If we know the direction in which a bed dips, we know also the exact bearing of its strike, but if we only ascertain the strike, we cannot also infer the direction of its dip, because it may incline to either side of the line of strike. In geological surveying, therefore, it is most important to observe the dip of all stratified rocks, and to note its direction accurately; it is also important to know its amount, or at any rate to ascertain the average angle at which any group of rocks is inclined.

Geological Map and Section.—Any exposure of rock at the surface, from which the nature and relative position of the beds can be ascertained, is called by geologists a *section*. The exposure may be an artificial opening, such as a quarry, mine, or railway-cutting, or it may be a natural section, such as the bank of a brook or the face of a cliff. These sections are what a geologist first seeks for and studies when he wishes to learn the subterranean structure of a district. By piecing together the information obtained from such isolated exposures he is able to construct a geological map of the district in which he is placed, and also to draw a continuous section through any part of it representing the arrangement of the rock-beds as they would appear if some giant hand were to make a vertical cut or trench through the country from the surface to the "sea-level."

Fig. 107 is a diagrammatic view of the Isle of Wight, illustrative of the appearance it would present if all the surface soil was removed, and the landslips of the Undercliff were cleared away, so as to expose the actual outcrops of the different beds over the southern half of the island. Moreover, a huge slice is supposed to have been cut out of the centre, so as to exhibit a vertical section through the island from north to south.



c, Chalk. f, Upper greensand. g, Gault. gs, Lower greensand. w, Wealden.

The beds which compose the southern half of the Isle of Wight have been divided as follows:—

5. Chalk at the top.	
4. Sand and sandstone	= Upper greensand
3. Blue clay	= Gault.
2. Sands and sandstones	= Lower greensand.
1. Clays and sandstones	= Wealden.

It is seen that the beds composing these groups are nearly horizontal in the foreground, but that as they are traced northward toward the centre of the island they begin to dip, the upper surface of each division being brought down to the level of the sea, and the topmost beds of the chalk passing beneath those which form the northern part of the island, and are named Tertiary.

Fig. 107 is the representation of a geological model in relief, but a geological map is only an ordinary map coloured so as to indicate the outcrops of the principal rock-groups. To construct such a map we proceed as follows:—Taking a good map of the district we wish to examine, together with a clinometer and a pocket compass, we search for all the natural and artificial sections. If the district be near the coast, the sea-cliffs will probably afford the best sections, and it will be desirable to ascertain the succession which they exhibit before attempting to map the country inland.

We will suppose that along a certain part of the coast we found a regular succession of beds, steadily dipping one under another in a certain direction: the rocky scar at low tide showing us the exact direction of their strike, the cliff section enabling us to measure the exact angle of their dip. Suppose, too, that the beds fell into five natural groups—1, clays and ironstones; 2, shales; 3, sandstones; 4, shales; 5, limestones; each set of beds having some peculiar characters of its own by which we should readily recognize them again.

When, therefore, we came to trace the beds inland and found a quarry where the sandstones (3) were exposed, we should naturally expect to discover indications of the shales above and below them somewhere on either side of the quarry. If further search in one direction disclosed

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the exact distance between the points where the upper and lower boundary lines of each formation cut the line of section, we can draw lines from these points with the observed inclination, in this case at 10° to the E.

When such a section has been constructed and drawn on a definite scale, the total thickness of the beds exposed at the surface can easily be calculated. Thus supposing the section, fig. 108, to be drawn on the scale of six inches to one mile, the thickness of the beds which come to the surface between the points *b* and *c* is shown by the line *c o* drawn at right angles to their dip; the length of this as measured by a scale is ⅝ths of an inch = 550 feet, while the breadth of ground occupied by their outcrops measures more than twice as much.[1]

Moreover, it is evident that we can also ascertain in the same manner the depth of any given bed below any point along this line of section. Suppose, for instance, that *b o* is a bed of ironstone, and that we wished to determine the depth at which it would be found in a perpendicular shaft below the point *d*. By scaling off the length of the vertical line under *d*, this depth is found to be about ⅜ths of an inch = 330 feet.

To make such a calculation it is not, of course, necessary to construct a section on a definite scale. It is only necessary to observe the angle of dip and to measure the distance of the given point from the outcrop of the particular stratum, and the desired depth can be ascertained trigonometrically by the solution of a right-angled triangle of those dimensions. To save trouble reference is generally made to a depth and thickness table, which gives the thickness measured at right angles to the dip, and the depth measured at right angles to the horizon, for every angle of inclination that any given bed will attain in a

[1] The term outcrop is often used for the tract of ground occupied by the outcrops of a set of beds of the same lithological character, such as make up what is called a sandstone or a shale. Properly speaking, however, the outcrop of the sandstone in fig. 108 is at *d*, and the tract of ground between *d* and 2, which is formed by the basset edges of the successive beds of sandstone, would be more correctly termed the *basset surface* of the sandstone, as distinguished from its natural surface, which is that covered by the overlying shale.

horizontal distance of 1,000 (feet, yards, etc.), measured directly across the strike.

DEPTH AND THICKNESS TABLE.

Horizontal distance = 1000.

Angle of Dip.	Depth.	Thickness.	Angle of Dip.	Depth.	Thickness.
1	17	17	16	287	276
2	35	35	17	307	292
3	53	53	18	318	309
4	70	70	19	345	326
5	88	87	20	366	342
6	106	105	25	469	423
7	123	122	30	580	500
8	141	139	35	705	574
9	160	157	40	842	656
10	177	174	45	1000	707
11	195	191	50	1190	766
12	214	208	55	1430	819
13	232	225	60	1740	866
14	252	242	65	2140	906
15	269	259	70	2750	940

Folds and Flexures.—Although beds sometimes continue to dip at nearly the same angle for several miles, yet it will generally be found that the whole series is bent into a great curve, so that in crossing their lines of outcrop we shall come to a point where the beds dip in an opposite direction. In low countries and broad table-lands these curves are sometimes only gentle *undulations*; elsewhere more decided folds and flexures occur, while in mountain regions the rocks are often bent or crumpled into a series of wonderful convolutions or *contortions*.

When these folds are on a large scale they are spoken of as anticlinals and synclinals; an anticlinal fold being that in which the beds are bent upwards into the shape of an arch or saddle, and a synclinal fold where they are bent downwards as into a trough. Such curves are always supposed to be bent upon an imaginary line which is called the axis of the curve; thus in fig. 110 the axis of a synclinal

curve is intersected at the point S, and the axis of an anticlinal curve at the point A.

Fig. 109 is an ideal plan of a district to show the way in which the outcrops of beds that are bent into anticlinals and synclinals are repeated on either side of the axis; it is

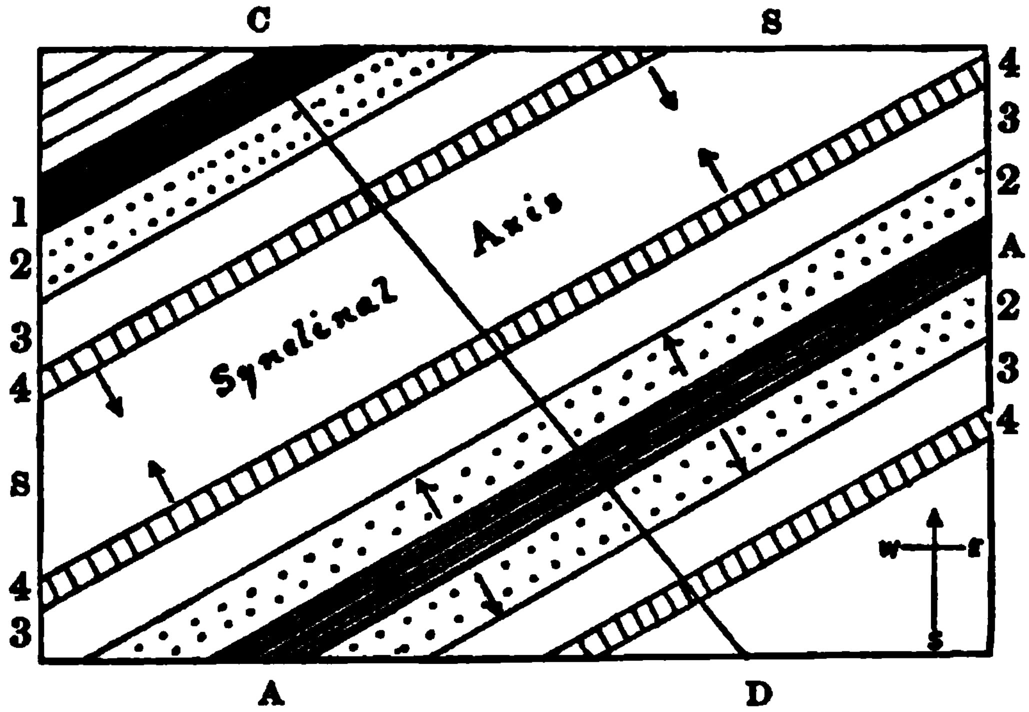

Fig. 109. Plan of Beds bent into an anticlinal and synclinal Curve.

part of a geological map in fact, markings or patterns serving the purpose of colours, and fig. 110 is a section across it along the line C D.

The beds are numbered from below upwards, and it is evident from inspection that the beds or groups of beds, 1, 2, 3, are repeated on either side of the synclinal axis, S S,

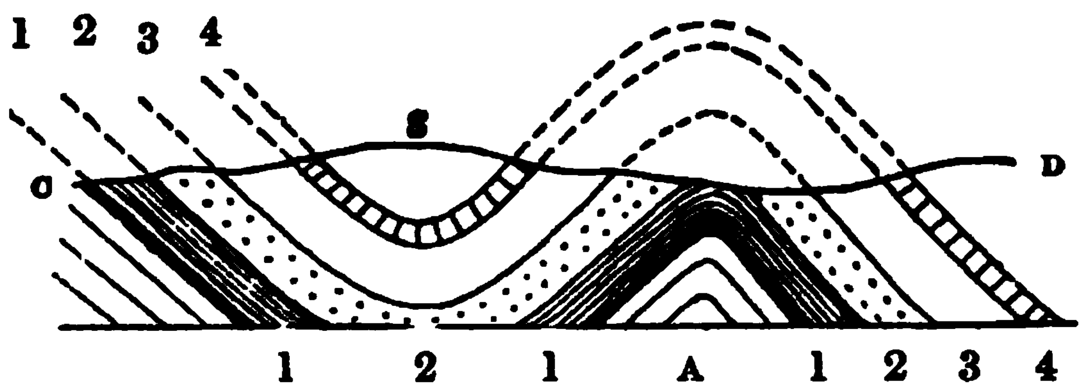

Fig. 110. Section along the line C D in fig. 109.

and that the groups 2, 3, 4, are repeated on either side of the anticlinal axis, A A. The arrows point in the direction of the dip, and the actual dips are seen in the section, fig. 110, where the line C D is the surface of the ground.

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centric bands crop-out to the surface; a section taken along any line across the periclinal would present a similar appearance. A periclinal with inward dips is often spoken of as a *basin;* but there is no recognized name for a pericline with outward dips. Periclinals which are much longer than they are wide may be spoken of as *cymboid* or *cymbiform*, that is, boat-shaped.

Monoclinal Curves.—When a set of horizontal beds is suddenly bent up or down into a sharp curve, and then

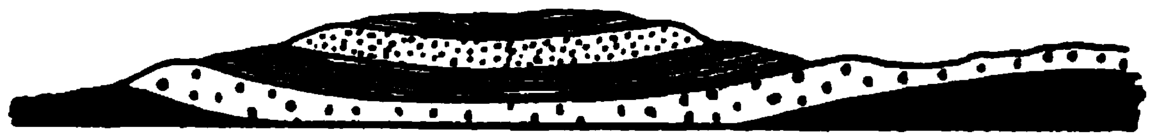

Fig. 114.

continued horizontally at a higher or lower level, the flexure is called a *monoclinal* or *uniclinal* curve. In the Isle of Wight, for instance (see fig. 107), the strata which form the hills in the southern part of the island are horizontal, but in the middle of it they suddenly plunge down at a very steep angle to the north, and then pass horizontally below the newer beds which form the low ground in the north of the island.

Even if the beds are bent back again by a second corre-

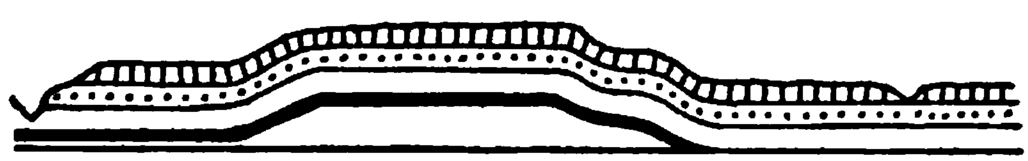

Fig. 115. Diagram of the Structure of the Kaibab Plateau, Colorado.

sponding flexure, so as to resume their former level, the form produced is not an arch, and though it might be called a flat-topped anticlinal, yet it is better to consider it as a combination of two monoclinals.

The region of the Colorado Plateaux in North America affords many instances of single and double monoclinal curves. The great features of the country, in fact, depend upon them, for the strata are horizontal except where they are bent upwards or downwards by such curves (see fig. 115). The country is thus divided into great blocks, several miles

in breadth and many miles in length, which have been unequally lifted, so that each differs from its neighbour in relative altitude. These blocks are bounded either by monoclinal curves or by displacements of the strata (=faults). Fig. 115 is a representation of the Kaibab block, copied from a woodcut in Major Powell's Report of his "Exploration of the Colorado." Its upper surface constitutes the Kaibab Plateau, which has a width of about 15 miles, and the strata of which it is formed are flexed down along both margins. The plateaux which compose the Colorado province reach altitudes of 5,000 to 11,000 feet above the sea, so that some of the *blocks* into which they are divided form true mountain ranges, such as the Uinta mountains.

Isoclinal Curves and Inversion of Beds.—These flexures are in some instances carried out so far, both on the small and large scale, that the beds are more or less inverted, and the lower surfaces of beds may be mistaken for their upper surfaces. Thus, in fig. 116, beds of shale

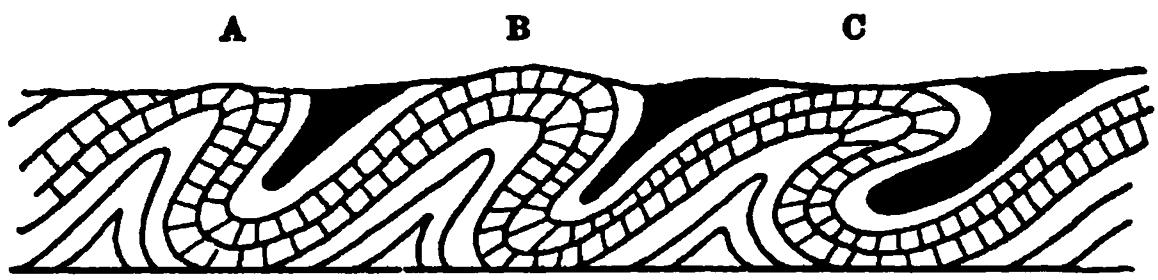

Fig. 116. Isoclinal Curves.

and limestone are bent into folds which are tilted over in one direction, so that the same bed is brought to the surface again and again, and an observer who walked over the ground might be deceived into thinking that he was dealing with a great thickness of beds all dipping uniformly in one direction, until he came across some quarry or open section which showed him the true structure of the country. A structure like this, where the folds are all inclined in one direction, has been termed *isoclinal*. At C the folding has been so great as to produce complete inversion. Such inversion may sometimes be actually seen in cliffs, as in North Devon, or in the sides of mountains, as in fig. 117, which is a sketch of the curved strata seen in certain Alpine peaks by Professor Bonney.[1] In other

[1] See his "Alpine Regions," p. 21.

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Part I., Chapter IV., the rocks must necessarily be subjected to great strains and pressures.

Though the earth as a whole seems to be extremely rigid, yet the rocks of which the crust is composed are by no means rigid; all clays and shales are more or less plastic, and many sandstones can be bent to a certain degree without fracture. Further, in many cases it is probable that the rigidity of the harder rocks has been caused by the compression of their mass. Hence we may conclude that the earth's crust is plastic within certain limits, and that folding and crumpling of its materials is possible under certain conditions.

It has been suggested that the mere vertical subsidence of a large area of the earth's surface will be sufficient to cause much flexure and contortion. Mr. J. M. Wilson has considered the results of subsidence,[1] and he argues that the borders of such an area must be subjected to lateral pressure and that the rocks of which it consists must be more or less folded and contorted. He therefore concludes that "*contortions* are the inevitable result of the subsidence of a *curved* surface."

If, however, we examine his results it does not appear that mere subsidence is capable of producing much compression. He constructed a table to show the amount of compression which would result from a given amount of subsidence, and from this it appears that if a circular region of the earth's crust measuring 690 miles across the surface were depressed through one mile (5,280 feet), its mass near the surface would be compressed into a space which had a diameter narrower by 633 feet. It follows from this that every bed of rock in this tract would be compressed to the amount of 1 foot in every 5,800 feet, and if the region were originally 2,760 miles across the compression would only be 1 foot in 6,000. This is so small an amount that it could all be expended in consolidation without flexure. Even if we assume a depression through four miles (21,000 feet) the amounts of compression are only 1 in 1,510 and 1 in 1,550 respectively, and this would go a very little way toward producing the amount of flexure

[1] "Geol. Mag.," vol. v. p. 206.

represented in the preceding figures; for an ordinary anticline like that represented in fig. 110 means a compression of 1 in every 3 feet, that is to say, 3 feet are bent on a chord of 2 feet, and 300 on a chord of 200 feet.

It is evident that for such results we require a much greater compressive force than is supplied by the mere depression of a curved surface; a greater force may be found in the secular contraction of the earth's crust, which follows from the cooling of the earth as a whole, but Mr. Fisher has shown that this could not do all the work that has been done, and he suggests that local pressures are exerted by convection currents in the liquid substratum upon the under surface of the crust. The consideration of this

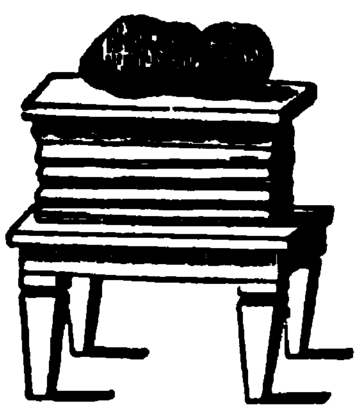

Fig. 121.

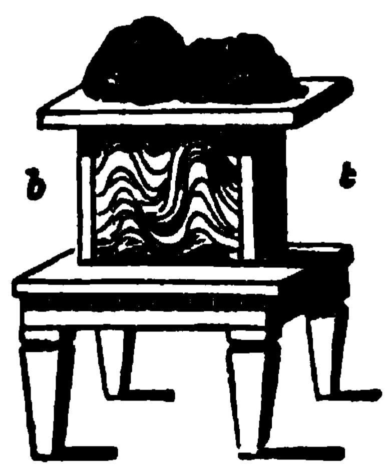

Fig. 122.

Sir James Hall's experiment.

matter must be deferred to a later chapter; at this stage the student must be content with the fact that plication can be produced by lateral pressure applied under the condition of great vertical weight, as was proved long ago by the experiment of Sir James Hall. He took pieces of differently coloured cloths, placed them horizontally on a table, and covered them by a weight (see fig. 121). He then applied pressure at the sides (*b b*, fig. 122), and found that while the weight was slightly raised the cloths were folded and contorted in a manner exactly analogous to the foldings and contortions observed in nature and illustrated by the preceding figures.

It must be remembered that the rocks which now appear so intensely crumpled and contorted have been buried under vast thicknesses of other rocks, and consist of various

beds of unequal hardness, which would offer unequal resistance to the force of lateral pressure. Moreover, the disturbances which caused the pressure have been repeated at many periods of geological history, so that the older rocks of a region that has been subjected to many such disturbances are naturally more bent and twisted than the newer beds.

Thus in the south and east of Ireland there are three great rock-groups, which have been named respectively the Cambrian, Ordovician, and Carboniferous; it can be shown that the rocks of the first were greatly disturbed and contorted before the deposition of the Ordovician, that the latter were similarly plicated before the deposition of the Carboniferous, and that the Carboniferous have also themselves been bent and folded into numerous curves. It is not, therefore, surprising that the Cambrian beds should in many places have been twisted into a confusion of knots and contortions, the complete unravelling of which would be a perfectly hopeless task.

There is, however, one kind of flexure which does not appear to be caused by direct lateral pressure, or rather it may be due to the conversion of a lateral pressure into a vertical uplift. This is monoclinal flexure, as illustrated by fig. 115. To this we shall recur in the next chapter.

CHAPTER IX.

FAULTS OR DISLOCATIONS.

1. Direct or Normal Faults.

IF great thickness of hard and solid rocks can be bent into the curves and contortions described in the last chapter, it may easily be conceived that a different application of the same force would be capable of cracking and breaking through them. We find accordingly that rocks are often traversed by great cracks or fissures, which pro-

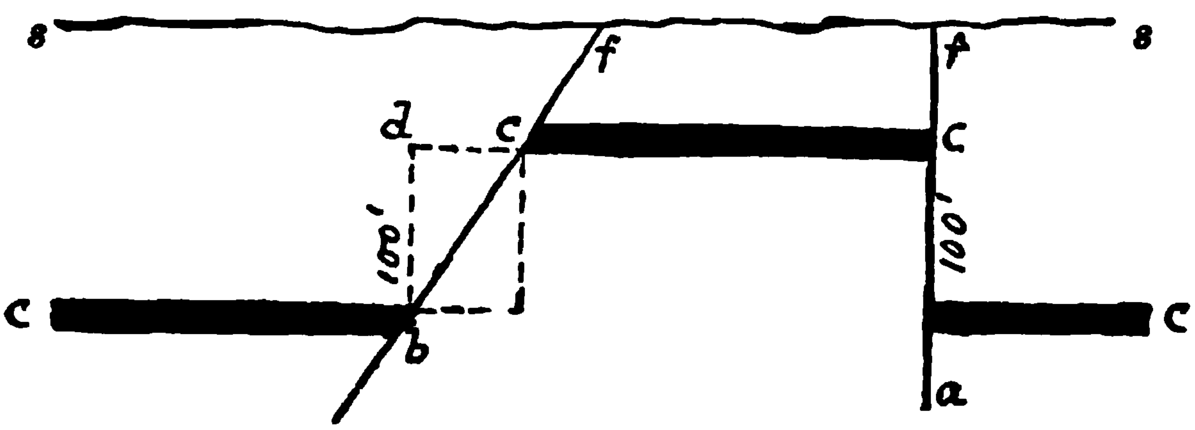

Fig. 123. Faults with the same amount of Throw.

duce not only a severance, but a displacement of the beds on either side, so that the separated portions are raised or depressed far above or below those with which they were originally connected. These fractures and displacements of large masses of rock are called *dislocations* or *faults*.

Throw and Hade of Faults.—Suppose fig. 123 to be a vertical section through a mass of rock dislocated by two faults, *s s* being the surface of the ground, and *c c* the course of a single bed which was once continuous, but has

been broken in two places by the two faults *f a* and *f b*. The two sides of any fault are spoken of as the *up-cast* and *down-cast* sides, though it is generally impossible to say whether the dislocation has resulted from the depression of one side or the upheaval of the other. In fig. 123, the mass resting upon the base, *b a*, may be supposed to have been bodily upraised.

To indicate the amount of displacement caused by a fault miners speak of its *throw*, and always measure this by the vertical distance between the broken ends of any given bed. Where the plane of the fault is vertical, as *f a*, in fig. 123, the amount of throw is easily measured along it; but when the plane of the fault is inclined to the horizon, as at *f b*, the throw is measured by prolonging the level of the given bed till a vertical line will reach its continuation either

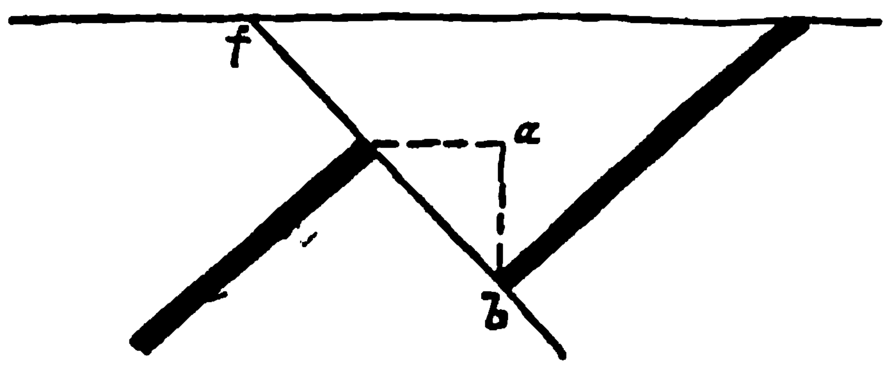

Fig. 124.

above or below it. In the case figured the throw of each fault is supposed to be the same, viz., 100 feet. The beds are also drawn horizontal, and when this is the case the amount of throw is also measured by the thickness of the beds displaced by the fault, *i.e.*, the thickness between *b* and *d*.

The student must observe, however, that the thickness of the beds displaced is not always a measure of the throw of a fault; when the beds are inclined, as in fig. 124, the vertical throw of the fault, measured from the level of one end of the broken bed to the level of its continuation, *i.e.*, from *a* to *b*, is evidently less than the the thickness of the beds displaced.

Miners also in describing the "width of a fault" mean the horizontal distance between the broken ends of a bed, namely, the distance *c d* in fig. 123. Geologists require a

more logical nomenclature, and often want to express the amount of stratigraphical displacement, as measured by the thickness of beds displaced, Messrs. Margerie and Heim[1] have therefore proposed to distinguish the three different measures of displacement above mentioned by the terms *vertical throw*, *horizontal throw*, and *stratigraphical throw*. Thus, in fig. 124 the vertical and horizontal throw are nearly equal, but the stratigraphical throw is much greater than either.

The amount of displacement or "throw" varies from a few feet to many hundred feet; faults involving a displacement of even several thousand feet having been found in some places, so that rocks of widely different kinds and ages are brought into apposition with one another. Thus, there is every gradation between cracks and fissures, which are merely enlarged joints with hardly any vertical displacement, and dislocations on the great scale above mentioned.

The inclination of the plane of the fault from the vertical, *i.e.*, the slope from *f* to *b*, in figs. 123 and 124, is called its *hade* or *underlie*. Thus we speak of the *dip* of a bed and the *hade* of a fault, but their angles are not measured in the same way. Faults usually hade at a high angle, only 20° or 30° from the vertical being common inclinations; and they are sometimes vertical, as at *f a* in fig. 123.

Open and Close Faults.—When faults traverse soft and yielding beds of rock, such as shales and thin sandstones or limestones, the fissures themselves are often mere planes of division no thicker than a knife-blade.

When faults traverse very hard and unyielding rocks, such as thick limestones or hard flagstones, and still more if they penetrate hard igneous or metamorphic rocks, the fissures are apt to be much wider and often very irregular. If the original fracture has taken place, not in one plane, but so as to produce two uneven and irregular surfaces, these surfaces, in sliding one over the other, are not likely to fit very closely, but will leave hollows and spaces here and there between the two walls of the fissure.

[1] "Dislocations de l'écorce terrestre," Zurich, 1888, p. 17.

It is true that the grinding process, as the rock-surfaces moved across each other, would often greatly diminish this irregularity, and, in soft rocks, probably obliterate it; but in hard rocks it is usual to find more or less space between the walls of the fault.

In all faults the contiguous surfaces are generally found to be polished and striated by the enormous friction which took place during the movement of one face across the other. These appearances are known by the name of *slickensides*, and it often happens that such slickensides occur on the surfaces of all the joints and cracks for some distance on either side of the fault, and are indicative of the jarring nature of the movement.

It must not be supposed, however, that such fissures are now open and empty. Sometimes they have remained open for a long time, and have been gradually filled up with deposits of crystalline mineral matter, in which case they are converted into lodes or mineral veins; these will be described on a future page. In other cases the spaces between the rock-walls are filled with a confused mass of fragments broken off the contiguous rocks during the movement of dislocation, mingled with sand and clay, produced by the attrition of these fragments against one another and the walls of the fault. This mass of fragmentary material is termed *fault-rock*, and is often consolidated into a kind of breccia.

Very large lumps and blocks of the broken beds are sometimes included in this way between the walls of a fault and serve to indicate the existence and direction of the fracture when it is being traced along the surface of the ground.

Single and Branching Faults.—In cases where the dislocation is affected by a single line of fault, it is clear that the beds must have been bent either upwards or downwards on one side of the fault, or upwards on one side and downwards on the other for a certain distance. Thus in fig. 125 some beds are supposed to have been cracked by the fissure *a b*, and the part *c* to have been bent down, but we might just as easily have supposed the part *d* bent up, or both operations to have taken place simultaneously. Without some such bending no dislocation could have occurred.

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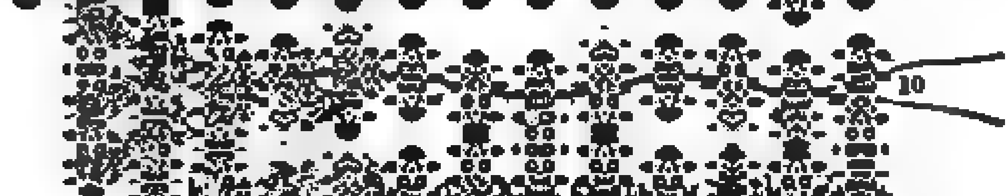

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been dropped down below, or squeezed up above the corresponding beds on the outside of them. In the plan fig. 127, let A B, C D, be two faults meeting in the point D, the included part, E, being depressed below the level of the outside parts. Even in this case, however, the beds inside the two faults must be bent down in the direction of E D, because, as the two faults end or die out at A and C, the

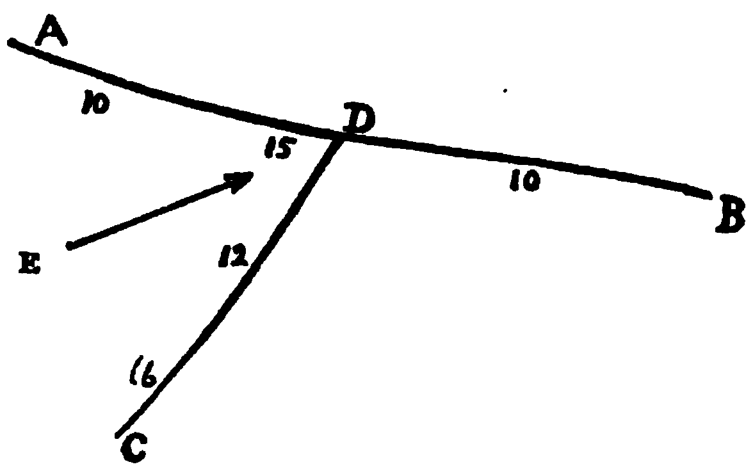

Fig. 127.

whole of the beds must be on the same level there, and gradually change that level in proceeding in the direction E D. The figures, as before, indicate the amount of throw.

In order to have any mass of beds entirely cut off on all sides from those that surround them, and wholly depressed below or raised above them on every side, it is obviously necessary that we should have at least three straight faults

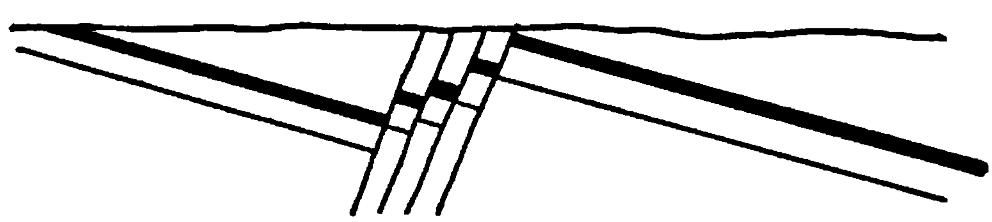

Fig. 128. Compound Fault.

or two curvilinear faults surrounding the fractured piece of ground.

Compound Faults.—A long powerful fault is often composed, in the whole or part of its course, of a number of parallel fissures, very close together, along a narrow band of country, breaking the rocks into a corresponding number of steps, as in fig. 128, which either *throw* all in the same direction, or else, having some steps in an oppo-

site direction, produce a *balance of throw* in one direction, so that it is treated as one wide fault.

Sometimes a set of strata are repeated again and again by a succession of parallel faults much farther apart than those in fig. 128, but hading in the same direction, so as to form a series of broad steps, as in fig. 129. Such step faults might lead an inexperienced observer, who traversed the slope from E. to W., to think that the outcrops of the bed *a* were those of four distinct beds, one passing beneath the other, whereas in reality they are portions of a single bed broken up and carried down to different levels.

If two neighbouring faults *hade* in opposite directions, the two planes must meet along some line below the surface, and will produce what is called a *trough fault.* In such a fault the *trough piece,* as it may be termed, is always let

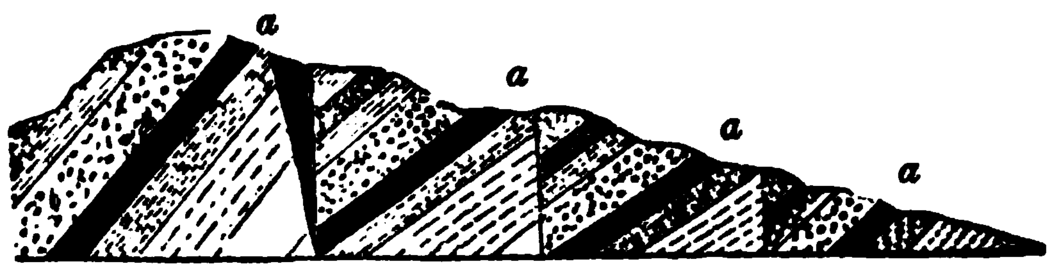

Fig. 129. Step Faults.

down like a wedge between the outer masses of rock, as in fig. 130.

The opposite faults of a trough may be either unequal in throw, as in the trough A, or equal in amount of throw, as in the trough B. In the former case the displacement along the line, *a, c,* affects the whole mass of the surrounding rock, as may be seen by tracing the beds *x* and *s* through the dislocations; in the latter case the displacements counterbalance one another, and affect only the trough-piece B, which is included between the faults.

Mr. Topley, however, has pointed out that the appearance of a trough fault may be caused by the displacement of one fault by another.[1] It not unfrequently happens that a district is traversed by two or more sets of faults produced at different times, and if one of the first set be intersected by one of another set, a complicated series of

[1] "Geology of the Weald," Mem. Geol. Survey, p. 238.

displacements may arise. Thus, in fig. 131, the bed, W, E, was first dislocated by the fault *a, b, c,* causing a simple downthrow on the W side at *b*. Subsequently a second line of fracture was formed, *d, e, f,* which hades in the opposite direction, so as to cause a displacement in the

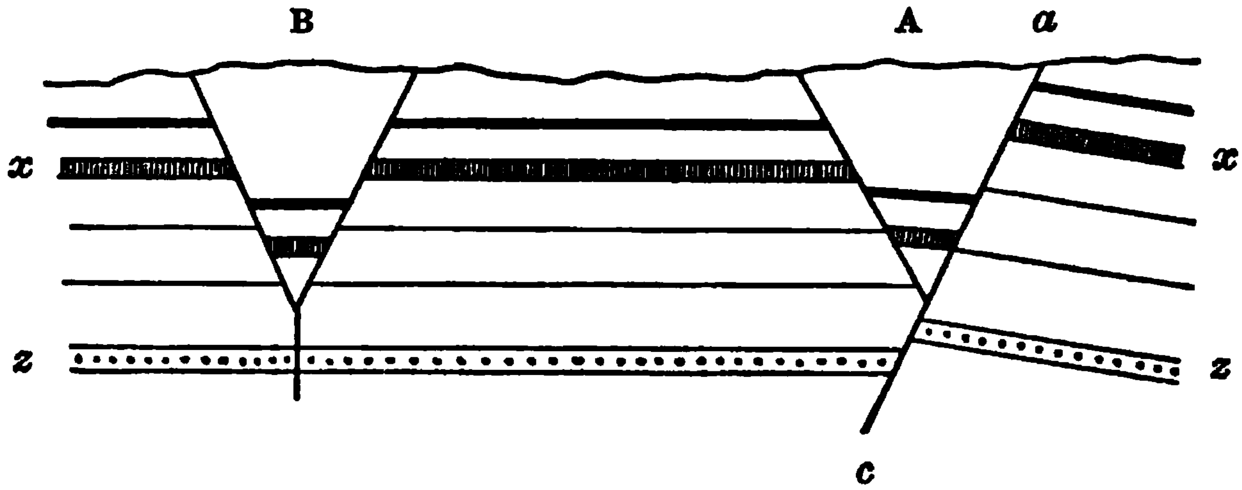

Fig. 130. Trough Faults.

plane of the first fault. In the figure this second fault is drawn with a downthrow on the E side, and the result of the two fractures is to produce a trough fault, for if the downthrow of the second fault was on the W side, it would be a reverse fault, which is of rarer occurrence.

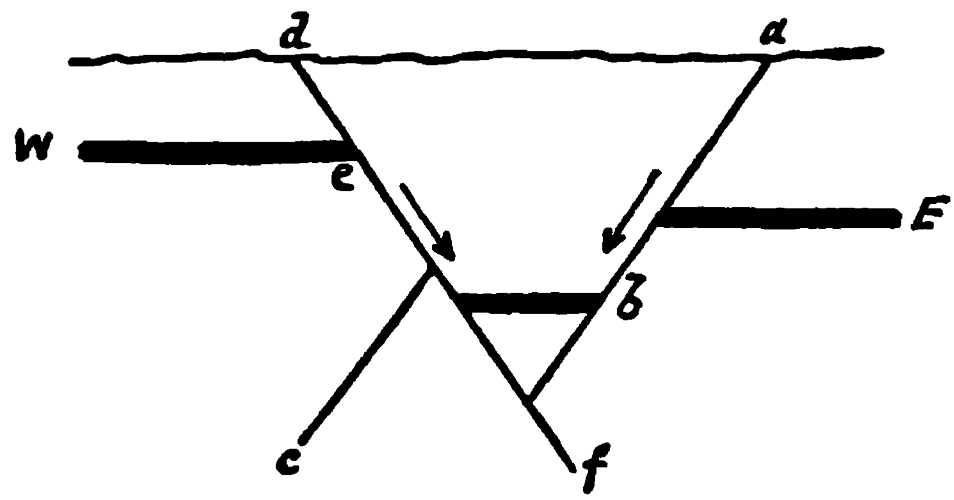

Fig. 131.

Downward diminution of Throw.—Where mining operations are carried to a great depth it has been observed that the throw of faults diminishes downward; that is to say, where a fault of the ordinary kind traverses a thick series of beds, the distance between the broken ends of a bed near the surface is greater than the distance between the ends of another bed one or two thousand feet

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squeezed, so that the thick coal lost much of its usual thickness on approaching the fault, and when it came within 10 or 12 yards of it, it was bent up perpendicularly, and the beds below it rose into the walls of the gate-road, and were cut off above by the red rock lying obliquely across them at an irregular line, the inclination of which to the horizon did not exceed 37°, somewhat as in the preceding figure (fig. 133), which is condensed from a rough sketch and measurement I made on the spot."

Effects of Faults on Outcrop.—Since rocks rarely remain horizontal over any considerable area, it is necessary to study the effects produced when a series of inclined or curved beds are traversed by a fault. It it obvious that the displacement must affect their outcrops, but the results produced will vary according to the following circum-

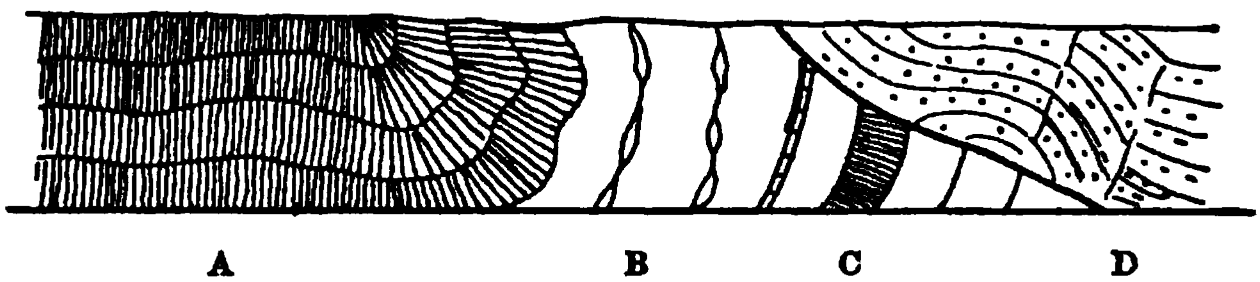

Fig. 133. Section through a Fault at Himley (after Jukes).
A, The Thick coal squeezed and bent upwards; B, Ironstones and shales; C, The Heathen coal; D, Permian beds.

stances:—1, The direction of the line of fracture; 2, the inclination of the strata; 3, the amount of the vertical dislocation. When the line of fracture cuts more or less directly across the strike of the strata, it may be called a *transverse* or *dip-fault;* and when it is nearly parallel to the strike of the beds, it is called a *strike fault*. Those which traverse the strike diagonally may be called *oblique* faults, and will produce a more complicated shift. Most faults, however, may be treated either as transverse or strike faults, and it will be sufficient, therefore, to describe the surface effects produced by these two classes under varying conditions of dip and flexure.

Transverse Faults.—If a set of beds, dipping at a given angle, and striking in a given direction, be traversed by a transverse fault, the effect of the vertical throw is to produce at the surface the appearance of a lateral shift. Let

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fault, so as to be prevented from cropping out to the surface at all. Thus in fig. 140 the outcrops of the beds numbered 4 and 5 are wholly concealed from view; and without some natural cross section like that in the figure, such a fault would be difficult of detection at the surface, because the surveyor would be apt to think that the beds 1, 2, 3, 6, 7, were in continuous succession, unless he were previously aware of the existence of the beds 4 and 5. The same result would be produced by a reverse fault hading in the opposite direction.

Magnitude and Extent of Faults.—Faults are sometimes dislocations of very great magnitude, both as regards amount of throw and the horizontal distance over which they extend. As a good instance of a strike fault, we

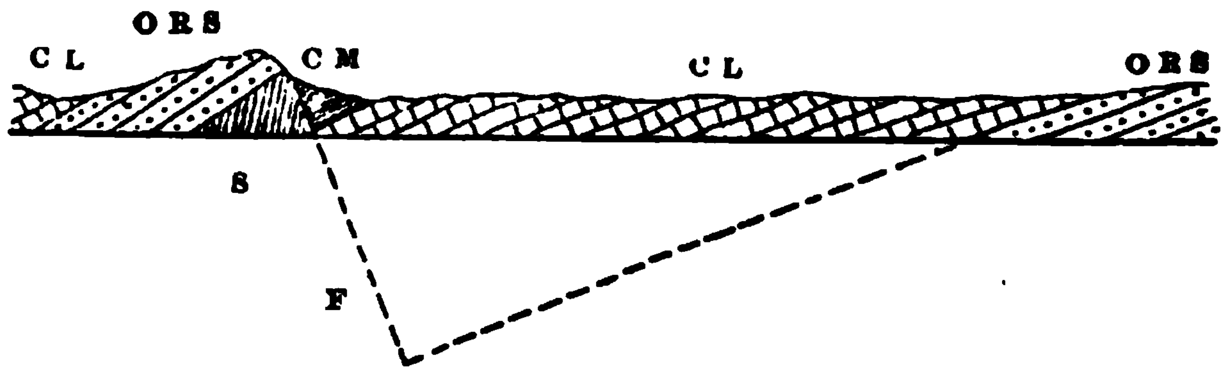

Fig. 141. Section through Tipperary (after Jukes).

C M, Coal Measures. O R S, Old Red Sandstone.
C L, Carboniferous Limestone. S, Silurian.

select that known as the Slievenamuck fault in county Tipperary, which is one of the largest in Ireland. This great fracture extends for a distance of 25 miles, and has a downthrow of nearly 4,000 feet.

Fig. 141 is a section across part of county Tipperary, and represents the dislocation produced by this fault. The rocks displaced by it are (1) certain slates and grits known as Silurian rocks, (2) reddish sandstones, called the Old Red Sandstone, (3) grey limestones, called Carboniferous limestone, (4) black shales belonging to the Coal-measures. On the south side of the fault the Old Red Sandstone is found rising steeply from beneath the limestone of the Vale of Aherlow and forming a hill called Slievenamuck, 1,200 feet high. In this hill its beds are

well seen, nearly from top to bottom, and their total thickness cannot be less than 1,000 feet. On the northern slope of the hill the bottom beds of the Old Red Sandstone are exposed, and may be observed to rest on the uplifted edges of the Silurian slates, which are seen for some depth along the face of the hill. But, on descending the hill a little lower, we come suddenly on to the Coal-measure shales dipping at a gentle angle to the south, and abutting directly against the Silurian rocks. These shales are about 800 feet in thickness and rest evenly on limestones similar to those in the Vale of Aherlow. Numerous beds of the same Carboniferous limestone crop out to the north, forming the plains of Tipperary, and making up a total thickness of about 3,000 feet. Finally, from underneath these limestones, the upper beds of the Old Red Sandstone again emerge, forming a second, but much lower ridge of hills, which may be called the Emly ridge. The amount of displacement, as measured by the united thickness of the beds which are affected by the fault, is 1,000 + 800 + 3,000 feet = 4,800, and we may, therefore, estimate the stratigraphical throw at about 4,000 feet.

In England a transverse fault known as the Yale and Bala fault runs from the lowland of Cheshire, through the Hundred of Yale in Denbighshire, through Bala lake and Tal-y-llyn to the sea coast near Towyn in Merioneth, a distance of nearly 66 miles. Its downthrow on the north-west side is estimated to be between 3,000 and 4,000 feet. A strike fault of equal magnitude runs along the western border of the Pennine Hills, from Brough in Westmoreland into Eskdale, for 130 miles, and is known as the Pennine fault. Its maximum throw is nearly 6,000 feet.

In Scotland a powerful fault crosses the country completely from sea and sea, and separates the more ancient rocks of the Highlands from the newer beds which form the Lowlands. Its length from Loch Lomond to Stonehaven is about 110 miles. Another great dislocation separates the Lowlands from the Southern Uplands, running for nearly 100 miles from Ayrshire into Peebles, and having an estimated throw of at least 15,000 feet in one part of its course.

Strike faults often form the boundary of one formation

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that the country consists of a number of long wedge-shaped masses of faulted strata, some of which have been carried for many miles over the others, and the original order of superposition is thereby completely inverted.[1]

Origin of Faults.

In endeavouring to explain the manner in which faults have been produced, it is necessary to consider each of the two great classes of faults separately, for it is obvious at the outset that displacements which differ in so many points are not likely to have been produced in the same way.

1. *Normal faults* may be regarded as adjustments of the strata to conditions which require them to spread out over a wider area than they originally covered. Now there

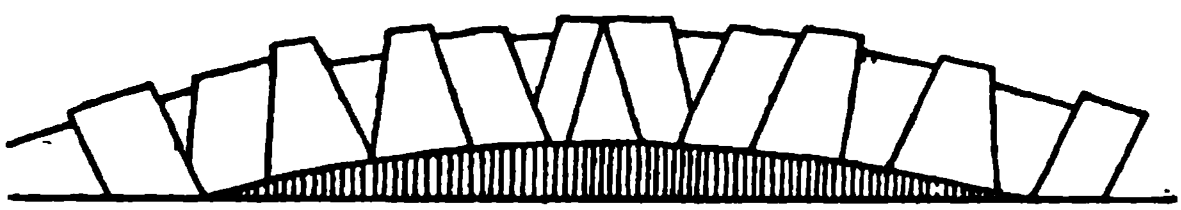

Fig. 145. Diagram of a Region faulted by upheaval.

is only one natural operation which tends to produce such conditions, namely, upheaval. When a portion of the earth's surface is upheaved, however that is accomplished, the upper layers of the crust are bulged out and compelled to stretch out over a larger surface. As the rocks composing these layers have very little elasticity, the tensions set up during upheaval must soon result in numerous fractures, and as the tension is greatest at the surface and less lower down, there will be a greater amount of fracturing in the upper than in the lower layers; moreover, as the severed blocks have to occupy a wider space, the fractures produced will be such as to enable the masses to settle down till they once more support each other (see fig. 145).

[1] Fig. 176 is a generalized section across the north of Scotland showing the long slices of faulted rock which have been thrust one over another from east to west. The base of the slice $m'm$ is a major thrust plane which cuts off three minor thrust planes below it.

During elevation also another influence comes into play which tends to reduce the mass or bulk of the rocks composing the raised area, and thereby relatively to increase the space over which they have to spread; this is contraction consequent on drainage and desiccation (see p. 390). The rocks are at the same time rendered more brittle and more liable to crack, and the fractures developed would become faults as the blocks settle down against one another.

We may therefore conclude that the simple elevation of a portion of the earth's crust would generate fractures which would be converted into dislocations of the kind known as normal faults.[1]

A case may be mentioned where simple upheaval seems to have produced a series of faults of the normal kind, such as would result from the settling down of a curved tract. The island of Barbados in the West Indies consists entirely of Tertiary strata. They fall naturally into three groups or series; the oldest are rocks which were formed in shallow water, the next series consists of consolidated oozes which were formed in oceanic depths, and the newest are coral limestones which envelope the surface formed by the two older groups, this surface having the shape of a flattened or low-arched dome. It is clear that after the formation of the oldest group of rocks the area subsided to a great depth (probably about two miles); after remaining for a long time as part of the ocean-floor, it was finally raised into the arched surface part of which forms the existing island of Barbados. Thus the history of the island invests its faults and flexures with a peculiar interest: now the oldest rocks are greatly flexured and contorted; the oceanic beds are only tilted or gently flexured, but they are cut up by faults and separated into blocks which are wedged in between masses of the older series. These faults do not affect the coral limestones, and they must, therefore, have been formed during the upheaval of the island to the sea-

[1] Mr. Mellard Reade has pointed out that wherever rocks have been expanded by heat, whether caused by a local rise of the isogeotherms or by the heat of rising columns of lava, when this heat decreases the rocks will cool and contract; faulting will thereby ensue, and the faulted blocks will subside on the side farthest from the source of heat.

level. There is no evidence of any lateral pressure or of any other kind of movement but upheaval since the formation of the oceanic deposits.

Let us now fix our attention on a single line of fault. Suppose that in the diagram, fig. 146, we have a section of part of the earth's crust of which A B is the surface and C D a deep-seated plane, subjected to pressures which cause

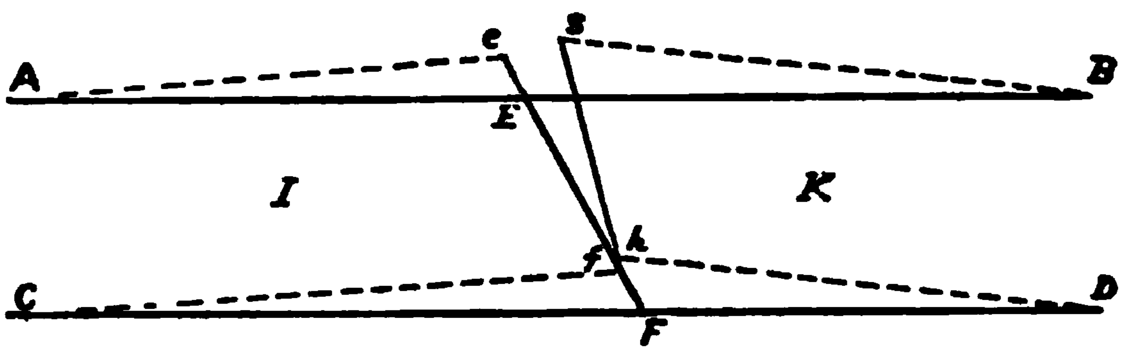

Fig. 146.[1]

upheaval of the part A B C D. If, then, a fracture take place along the line E F, it is obvious that the mass I will present the broader base C F for the upheaving force to act upon, and also that this mass grows smaller towards the surface; while the mass K has the smaller base and the wider surface. It is clear, therefore, that it is easier to

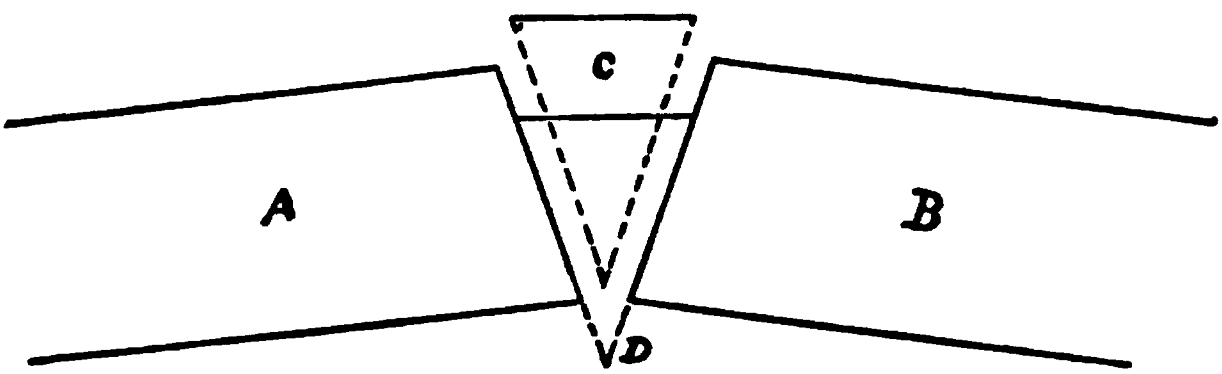

Fig. 147.

lift the mass I into the position A C *e f*, than the mass K into the position *g h* B D. The mass I, therefore, will become the upthrow side of the fault, while the mass K will occupy a lower level, and will form the downthrow side. Hence the rule given on p. 453, that a fault generally hades on the downthrow side.

[1] This figure is copied from that in Jukes' "Manual of Geology," and the explanation is abridged from that given by the same author.

This is yet more clearly perceptible if we suppose two such fissures, as in fig. 147, inclining towards each other, since, if we conceive the included piece, C, to be elevated into the position indicated by the dotted lines, it becomes wholly unsupported, unless we suppose huge injections or dykes of igneous rock to issue out along each fault, which would remove the case from the class of fractures we are at present considering. In the case represented by the fig. 147, the masses A and B would both be elevated, and the space between them would be widened, so that the mass C would be let down along the planes of the two faults, both of which would thus hade to the downthrow.

In this case, also, we have the key to the explanation of certain trough faults. The reader must recollect that the figs. 146 and 147 are merely diagrams to assist his comprehension, and not actual representations, which would necessarily exhibit a much greater amount of complexity.

The general conclusion that normal faults are produced by the slipping and adjustment of fractured blocks during upheaval is confirmed by the fact that faults have been actually formed with the accompaniments of upheaval and earthquake shock (see p. 60), the earthquake being, apparently, the jar from the sudden yielding along the fault plane.[1]

2. *Reversed and thrust faults*, as already stated, must be regarded as adjustments which enable the strata to occupy less horizontal space than they did originally, and it is also clear from their mode of occurrence in Scotland that this has been effected by the piling up of the fractured strips of rock one over another, as in the diagram, fig. 148.

In this figure *a b* represents the position of a single stratum before the faulting took place, and *a c* the position of the severed fragments after the faulting, each broken piece having been pushed up the plane of the fracture in front of it. To get the arrangement shown in figure we have only, then, to imagine the shearing off of the subjacent and superjacent continuations of the series by the two thrust planes T, T.

[1] See C. Davison on British Earthquakes, "Geol. Mag.," 1891, pp. 67 and 306.

The only force which could accomplish such an adjustment is a lateral thrust. It must, in fact, be the extreme development of the lateral pressure which produces isoclinal flexure, and the frequent association of isoclinal flexures and reversed faults makes it clear they are due to the same kind of impulse. The manner in which this force is supposed to be developed will be discussed in Part III.

Connection between Faults and Folds.—It has been said that in a district which is much broken by faults the rock-masses between them are not usually much contorted. This may be true to a certain extent, but must not be interpreted to mean that folds and faults are not usually associated. On the contrary, there is a close relation between them; and the two great classes of faults (*strike* and *transverse*) may be regarded as connected respectively with the two classes of flexures described in the last chapter. In the midland counties of England, where the beds are bent into two sets of undulations, one parallel to, and the other transverse to the general strike, there are also two sets of faults, similarly related to one another. In the Wealden area of Kent and Sussex the majority of the faults have the same strike as the principal folds, viz., from east to west.[1]

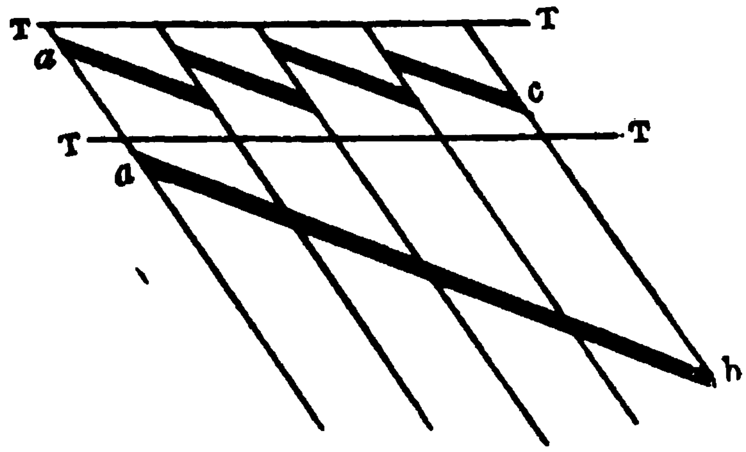

Fig. 148.

It is possible that many faults are only surface phenomena, and that, if traced downwards into the earth, they would be found to pass into anticlinal or synclinal flexures. It is more likely, however, that the relation between them

[1] Topley, "Geology of the Weald," Mem. Geol. Survey, p. 237.

is in most cases an indirect one, that planes of weakness running more or less parallel to the axes of the folds are produced in the process of flexuring, and that these are developed into fractures and faults by subsequent movements.

Between faults and monoclinal flexures there seems, however, to be a closer connection, for these often pass laterally into one another; that is to say, the same line of displacement may be a flexure along part of its course and a fault along another part, the flexure gradually becoming a fracture by the severance of the upper from the lower limb of the curve. It is possible that monoclinal flexure results in many cases from the displacement of a deep-seated subterranean plane, which separates two very dif-

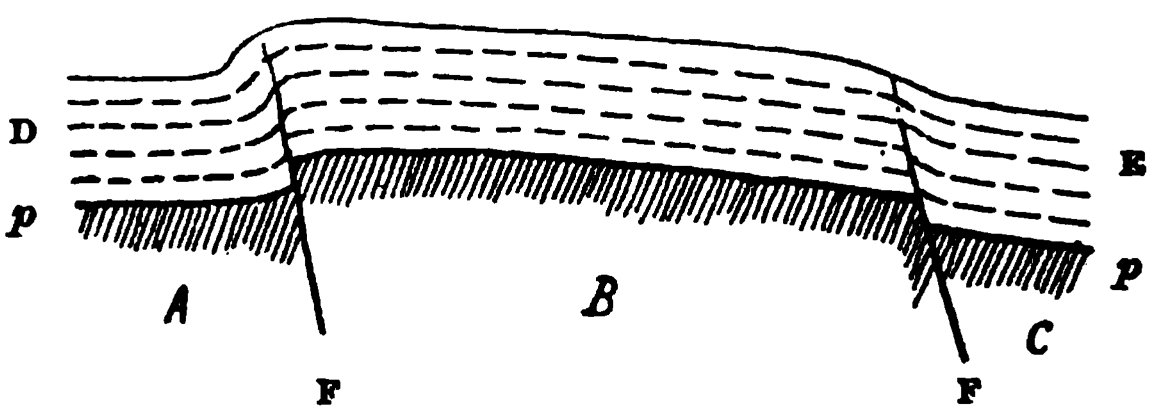

Fig. 149. Faults and monoclinal folds.

ferent series of rocks. Suppose A B C in fig. 149 to be portions of a mass of ancient rocks which were indurated, flexured, and faulted before the deposition of the newer series D E, the line *p p* having been a horizontal surface of erosion and the series D E being disposed originally in horizontal strata above this plane. In the figure it is supposed that, under lateral pressure, the lower mass has given way along the pre-existing faults, F F, and that the block which lay between them has been forced to move upward, so as to cause the vertical uplift of the superjacent beds. It is evident that this tract will be bounded by faults or flexures; whether the one or the other is produced will depend partly on the thickness and pliability of the strata forming the cover, and partly on the amount of local uplift; and it is quite conceivable that the displacement might be partly by faulting and partly by flexure.

Mineral Veins.

In studying faults our object has been chiefly to describe their effect in dislocating the beds which they traverse, and only brief mention was made of the minerals which they occasionally contain. It was stated, however, that where faults traversed hard rocks, they are generally more or less open, the walls having been kept apart in some places by their own inequalities. The same is the case with many large cracks and joints in limestone rocks which have been widened by the action of water.

Now, in many districts, these open fissures have become the repositories of minerals that have been subsequently introduced into them, and they are then termed *lodes* or *mineral veins*.

The minerals they contain are usually in a crystalline form, and consist of quartz, calcite, barytes, or fluor-spar, together with the ores of one or more metals, such as lead, copper, zinc, antimony, or silver. It is to the metallic minerals that the miner, of course, chiefly looks; and he generally speaks of the earthy minerals as the *gangue* or *vein-stuff*. The mineral contents of a vein are sometimes confusedly dispersed through it, the vein-stuff occupying the chief part of the space, and the ore occurring either as disseminated crystals, or in *nests* or *strings*. Sometimes there appears a regular arrangement of the various substances: the cheeks or walls of the lode being lined with a layer of crystals of one kind of substance, with their points or apices turned inwards, each of these layers being covered by a crystalline layer of another substance, evidently deposited upon the first; and, after two or three such alternations, a rib of ore is found in the centre (see fig. 150).

This kind of structure seems to involve the idea of successive depositions of the different coatings or linings of the vein, the central rib of ore being the last or newest. In some cases, it appears that fresh cracks were made by subsequent movements, and that new deposits were found in these openings, slickenside surfaces often occurring on their sides.

The term "lode" is the name applied to such mineral veins in the West of England; but in the northern parts

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ore being found in the former and another in the latter. Where the date of the cross course is newer than that of the lode, which is often the case, it is easy to understand this difference. When, however, the two veins are contemporaneous, as sometimes happens, it is not so easily understood, but may perhaps be due to differences of temperature in the stream of water by which the minerals were introduced into the fissure.

If a mineral vein be inclined from the perpendicular (and they are seldom quite vertical) it is obvious that any subsequent fracture, producing dislocation, will displace the first-formed lode just as if it were a bed. In the same way its outcrops at the surface will appear to be shifted laterally. Thus in fig. 151, *c c* is a right lode, the outcrop of which is shifted by the fissure or cross vein, *v v*. With regard to such intersections, Mr. Jukes observes that "if

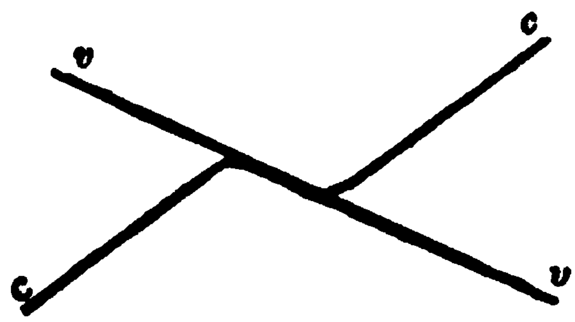

Fig. 151.

the contents of the right vein are distinctly broken through by the cross course, it is certainly strong evidence that the cross course is newer than the right running vein. If the contents of the cross course be continuous across the interrupted contents of the right running vein, the evidence becomes still stronger;" but it appears that such is not invariably, though very frequently, the case.

It should here be remarked that the hade or inclination of lodes is always calculated from the vertical, as with faults, and not from a horizontal line, as with beds; a slight hade, therefore, answers to a high dip, the one being the complement of the other, a hade of 10° being a dip of 80°.

By what processes the various minerals have been introduced into veins is a subject on which much has been written, but little is certainly known.

Sir H. de la Beche has pointed out that where warm

water is rising from great depths through narrow fissures, it must lose a large amount of heat as it approaches the surface. Consequently those substances which are only soluble at high temperatures, such as silica and many metals, would crystallize out of solution, and would be deposited on the walls of the fissure.

This theory finds support in the fact that mineral veins are being actually formed in certain volcanic districts at the present time. Sulphur Bank, California, is one locality where such vein-formation has been observed.[1] Hot springs, solfataras, and fumaroles are here abundant, and the deposits are clearly due to the uprising alkaline or solfataric waters. At a certain depth below the surface, beyond the influence of atmospheric agencies, the cracks and fissures in the rock are filled with a hydrous silica (opal) in a soft cheesy condition, generally streaked and clouded with cinnabar (sulphide of mercury). In other parts of the mine the silica has consolidated into chalcedony, and the cinnabar is found sometimes in layers alternating with the silica, sometimes lining or filling fissures by itself. Here, therefore, veins with quartz vein-stuff and metallic ore are now actually in process of formation.

It has been found that some relation exists between the mineral contents of a vein and the nature of the rock which it traverses. Some Cornish lodes contain copper ore where the walls consist of slate, and tin ore only where they are of granite.[2] This fact may, however, be explained by supposing that different rocks are capable of determining the deposition of different minerals on their surfaces under the influence of terrestrial electricity.

[1] See paper by Leconte and Rising in "Amer. Journ. of Science," Ser. 3, vol. xxiv. p. 23.

[2] J. W. Henwood, "Trans. Geol. Soc. Corn.," vol. v. p. 190.

CHAPTER X.

IGNEOUS ROCKS REGARDED AS ROCK-MASSES.

THE different kinds of Igneous rocks, regarded from a lithological point of view, as hand-specimens in which different minerals can be seen either without or with a microscope, were described in Chapter III. In this and the next chapter we shall treat them as rock-masses and describe the positions which they occupy in the crust of the earth.

A very little practical experience of igneous rocks in the field teaches us that the most important point in which such rock-masses differ among themselves is the relation in which they stand to the stratified rocks by which they are surrounded. In relation to the latter igneous rocks are either *intrusive* or *interbedded;* that is, they have either been injected or intruded among previously existing strata, or else they are interbedded with strata which were formed around the active volcano.

There is another point of difference which is important, though not always so easily ascertained. Most igneous rocks have been in direct connection with volcanoes, and may be called *eruptive,* but the subterranean reservoirs from which they issued form, when cooled and crystallized, deep-seated *plutonic* or *hypogenous* masses. It is often difficult to say whether an isolated mass of granitoid rock was or was not connected with an active eruptive vent, but there is good reason to believe that many masses of crystalline igneous rock are the terminal portions of intrusive magmas which never reached the surface, but consolidated under a thick cover of stratified rock.

In viewing the igneous rocks as constituent parts of the earth's crust, it seems most natural and convenient to proceed from the known to the less known. Commencing with the description of the remains of actual volcanic orifices which can be interpreted by our knowledge of recent volcanoes, we may proceed to consider the more or less circular intrusive masses which were once connected with such vents; thirdly, their prolongations in the form of dykes, sills, and laccolites; and lastly, the interbedded lavas which occur in acient volcanic districts.

A. Remains of Ancient Volcanoes.

Extinct Volcanoes.—It was stated on p. 136 that modern volcanic cones, in common with all other terrestrial surfaces, are wasted by rain and frost, so that their flanks are trenched by deep gullies and ravines. As long as the volcano continues to be active, these losses are more than counterbalanced by fresh ejections, but when volcanic activity finally ceases it is evident that such losses cannot any longer be made good; the mountainous pile of ashes and lava-flows will slowly succumb to the continued action of the detritive agencies until nothing but a worn-down stump is left to mark the existence of the former volcanic cone. So long, however, as the district is not submerged beneath the sea-waves, some remnants of the old volcano will generally survive, and the existence of such extinct volcanoes in various stages of ruin and decay has already been mentioned.

Some still preserve their cones and craters, and the lava-streams proceeding from them are still rough and bristling, though they have never been active during historic times; others have had their cones and craters more or less obliterated by the action of rain and frost, and the country around them has been so lowered by general detrition, and so altered by the erosion of valleys, that the lava-streams which originally ran down the lowest ground they could find, are now found in detached remnants on the top of ridges and plateaux.

No better example of such extinct volcanoes could be

cited than those of Auvergne, in central France, some of which are shown in the plate at the end of this volume.[1]

The Limagne d'Auvergne may be described as an extensive plain, chequered with low hills of fresh-water marl and limestone which are capped with portions of lava-flows (Plate II., fig. III.). This tract is enclosed on the east and west by two parallel ranges of granite and gneiss, that to the westward forming a lofty plateau of granite, rising to a height of about 3,000 feet above the sea, and 1,600 above the valley of Clermont. This granite plateau supports a chain of volcanic cones and dome-shaped hills, about seventy in number, varying in altitude from 500 to 1,000 feet above the plateau and forming an irregular range nearly 20 miles in length and about 2 in breadth. The highest point of this range is the Puy de Dome, which rises to a height of 4,000 feet. Many of the cones retain the form of well-defined craters, and their lava-currents are as perfect as those of Vesuvius. Plate II., fig. II., is a view of part of the southern chain of Puys, as these hills are locally termed; several of them are broken down on one side and lava-currents have issued from the gap.

One of the most remarkable cones is the Puy de Come, which rises from the plain to the height of 900 feet; its sides are covered with trees, and its summit presents two craters, one of which is 250 feet in depth. A stream of lava has issued from its base, but at a short distance, having been obstructed by a mass of granite, it has branched and flowed round it; thence it can be traced along the granitic platform and down the side of a hill into an adjacent valley, where it has dispossessed a river of its bed, and constrained it to work out a fresh channel between the lava and the granite of the opposite bank.

Mont Dore (Plate II., fig. I.) is a mountainous tract, the highest portion of which is about 6,000 feet in altitude. The dotted outline in fig. I. shows the presumed form of the crater when in activity, but the crater is ruined and broken down, and consists of a group of seven or eight

[1] The following description of the volcanoes of Auvergne is abridged from that in Mantell's "Wonders of Geology," and founded upon Mr. P. Scrope's work on the "Geology of Central France."

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The actual site of an old volcanic vent is sometimes manifested, even after the total destruction of the cone itself, by the exposure of the cylindrical pipe which once terminated upwards in the central orifice or crater of the volcano. This pipe or chimney, when disclosed by denudation, is called a *neck*, and is always filled with some kind of volcanic rock, either by a plug of solidified lava, or by a mass of volcanic agglomerate. Such necks vary in diameter from a few yards to several hundred feet.

A vertical section of a neck filled with crystalline rock might be mistaken for a dyke, but a horizontal plan or surface exposure would show that it is a round or oval pipe and not a long fissure. In the case of necks filled with agglomerate the nature of the material would prevent such a mistake being made. In most cases the surrounding rocks are partially baked or altered like those in contact with all other intrusive masses, but there is one class of necks in the neighbourhood of which no such alteration has taken place.

There are several districts in the British Isles where numerous volcanic necks exist, and where they have been so dissected and laid open by coast erosion that their relations to the surrounding rocks can be examined in detail. County Antrim, in Ireland, and the shores of the Firth of Forth in Scotland, are two of these localities.

Fig. 153 is a plan of a small neck of porphyrite in Haddingtonshire, as exposed on the shore, near the mouth of the river Tyne.[1] Its longest diameter is about 300 yards, and a section through it would probably have the appearance shown in fig. 154. The beds of sandstone through which it is drilled are baked and hardened, and it will be noticed that they are bent down so as to dip everywhere towards the central plug of lava. Near the neck the dip is often between 40° and 50°, but at a little distance it is only 15° or 20.° This inward dip of the strata surrounding a neck is of frequent occurrence, and may be attributed

[1] "Geology of East Lothian," p. 40.

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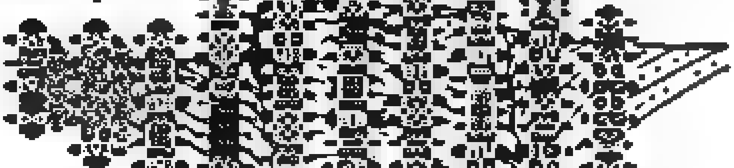

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and porcellanized, while the basalt is bordered by a band of white trap from 2 to 3 feet thick. Still farther westward are several other examples of small necks filled with agglomerate, and projecting through the shales and sandstones which form the shore, so that the observer standing in the centre of one of them can easily take in the whole of its circumference. These must have been mere pocket-editions of volcanoes, and were probably only blowholes of dust and stones, for the shales in contact with them are not altered like those around the basalt necks.

The alteration of the stratified rocks in contact with necks now filled with agglomerate, must have been effected by the previous passage of molten lava through the pipe, for it is evident that the passage of hot gases, dust, and stones could hardly produce much effect on its walls. It

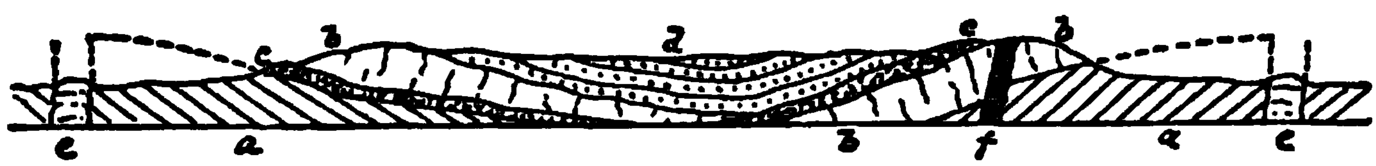

Fig. 155. Section across the Volcanic Basin of Ayrshire.

a, Older rocks. *b*, Sheets of porphyrite. *c*, Beds of tuff.
d, Red sandstones. *e*, Volcanic necks. *f*, Dyke of basalt.

can sometimes be demonstrated that this was the case, as in the following instance occurring in Ayrshire, and described by Professor J. Geikie.[1] "Outside the volcanic ring (of interbedded ashes and lavas) there occurs a number of small rounded hills or hillocks consisting of a coarse red volcanic agglomerate. These hills are true volcanic 'necks,' each representing a former crater or focus of eruption. . . . They descend vertically through the Coal-measures like so many huge pipes, sometimes standing on lines of fault, while the coal near them is altered. In one case, that of Helenton Hill, near Monkton, I found the sides of the neck still partially crusted with a mass of rough scoriaceous melaphyre—the remnant of the slaggy scoria which once coated the walls of the volcanic orifice."

The Fifeshire examples, and others where the contiguous strata are unaltered, find a parallel in the extinct volcanoes

[1] "Geol. Mag.," vol. iii. p. 246.

of the Eifel, of which Sir Charles Lyell says,[1] "The most striking peculiarity of a great many of the craters above described is the absence of any signs of alteration or torrefaction in their walls, when these are composed of regular strata of ancient sandstone and shale. . . . . There is indeed no feature in the Eifel volcanoes more worthy of note than the proofs they afford of very copious aeriform discharges, unaccompanied by the pouring out of any melted matter, except here and there in very insignificant volume."

Bosses.—These are intrusive masses of igneous rock, from which the upper parts have been removed, and which are so far dissociated from any erupted rocks as to make it doubtful whether they were connected with volcanoes or not. Many of them are probably the basal parts of volcanic necks, but others may be parts of intruded masses which were arrested in their upward progress, and did not succeed in reaching the surface. Consequently, it is usual to speak of all such intrusions as *bosses* until some evidence of their true relations can be obtained.

Bosses generally consist sf coarsely crystalline rock, but sometimes they are partially or wholly composed of compact rock with a porphyritic structure; and it is often observable that the interior portions are much more largely crystalline than the outer portions of the mass.

An excellent instance of this came under the writer's notice at Dalmeny on the Firth of Forth, where the Carboniferous shales and sandstones are interrupted by an irregularly oval mass of igneous rock more than a mile in width. Its outer portion is an ordinary fine-grained dolerite, but towards the interior the crystals of augite and felspar became very distinct, and the central portion is as coarsely crystalline as any granite, some of the augite crystals being an inch in length; scattered crystals of quartz and mica increase the granitoid aspect of the rock, which may perhaps be designated as an augitic gabbro.

They usually appear as irregularly round or oval masses, forming conspicuous hills, and the stratified rocks around them are always more or less baked and altered. On a

[1] "Elements of Geology," eighth edition, p. 674.

geological map they appear to take the place of so much stratified rock, and seem to have cut or bored their way upward without much disturbing either the strike or the dip of the strata in which they occur.

The eminence called Barrow Hill, near Dudley, may be cited as an instance. This mass consists of coarse basalt or dolerite, and its surface exposure forms a pear-shaped area (as shown on the Geological Survey map), but below the surface it widens out in the manner suggested diagrammatically in fig. 156, sending out tongues into the adjoining coal-measures, which are baked and charred.

One of the most striking series of bosses is to be found in Carnarvonshire, and good evidence has recently been obtained for considering them to be the basal portions of the volcanic vents from which were erupted the great

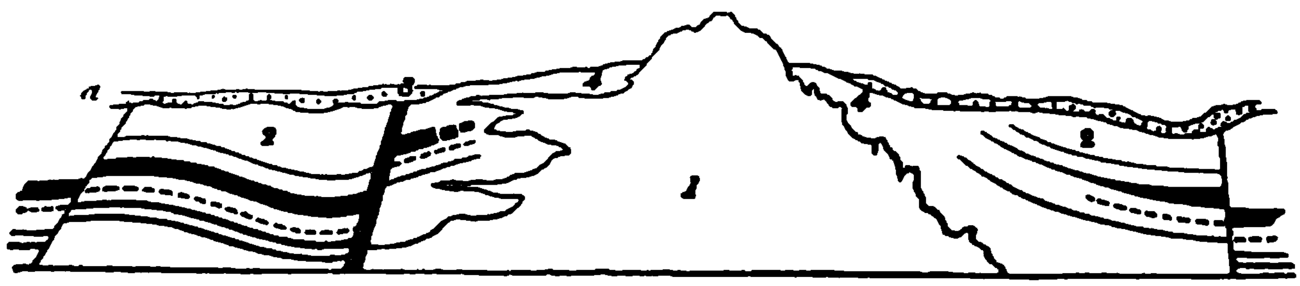

Fig. 156. Intrusive Mass of Dolerite at Barrow Hill, Dudley.
1. Dolerite. 2. Coal-measures. 3. Faults. 4. Altered coals, etc.

series of volcanic rocks that form some of the highest and most picturesque mountains of North Wales. These bosses occur at intervals along a line which runs from Penmaenmawr, near Conway, through the Snowdon range into the peninsula of Lleyn, a distance of forty miles; they include the great domes of Foel Fras and Mynydd Mawr and the remarkable group of smaller eminences which rise from the coast near Yr Eifl and Nevin. Their real connections were first pointed out by Mr. A. Harker,[1] from whose excellent description, and from the still more recent notice by Sir A. Geikie[2] the following accounts are taken.

The largest and most important of these bosses is that of Foel Fras, which rises to 3,000 feet above the sea, and

[1] "The Bala Volcanic Series of Carnarvonshire," Sedgwick Prize Essay, 1889.
[2] "Presid. Address to Geol. Soc.," 1891, p. 125.

Fig. 157. View of the Mountains of North Carnarvon, from near Llandudno.
This and Fig. 158 are reproduced from the "Pictorial Itinerary of North Wales."

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dome-shaped hills or prominences; they pierce the stratified rocks, seriously interfering with the general dip and strike. Many of them are flanked by felspathic lavas and tuffs of contemporary date; and he therefore regards them as the stumps of some of the volcanic necks which supplied the melted and fragmental materials.

Large areas of Granite.—A remarkable series of granite bosses is found in Devon and Cornwall which seem to exhibit another stage in the dissection of volcanic centres. The best known of these is the granite area of Dartmoor, which occupies a space of about 240 square miles, and rises to a height of 2,000 feet above the sea. Notwithstanding its great size, its relations to the surrounding rocks are similar to those of the bosses above described.

It penetrates and alters rocks belonging to two different systems, viz., the Carboniferous and Devonian. Its intrusion, however, has not everywhere brought up the lower (viz., the Devonian) rocks to the surface; neither does it appear to have acted in any sense as a geological axis or centre of elevation, but it cuts across the boundary line between the two sets of rocks, breaking through them in a large irregular mass, which rises into hills of considerable height and clearly occupies the place of so much stratified rock (see fig. 160).

Considering the great size of this mass of granite, its metamorphic action on the contiguous rocks is not very great; this does not generally extend to a greater distance than a quarter of a mile, but varies according to the nature of the rocks; and where the beds dip off the granite, as they do on the north-east side, it extends farther into them.

It has been suggested that the granite of Dartmoor is the basal core of an old volcano, and there are facts which favour this view, but if so, all the superficial and eruptive portions of the mass have been broken up and destroyed, and the neck has been worn down to the very base of the igneous protrusion, so that its present surface is probably not very far above the general surface of a wide-spread granitic mass which was the magma or reservoir whence the Dartmoor material was derived.

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dip or strike of the slates into which they penetrate. On this point Mr. Jukes remarks: "The entire want of conformity between the irregular outline of the surface of the granite and the position of the aqueous and metamorphic slates about it has, I believe, been the origin of much scientific and some practical misapprehension. Mr. Curwen Salmon was kind enough to send me some time ago an instance of the latter from one of the Cornish mines, where, trusting to the apparent dip of the slates, a shaft was sunk which was expected to be wholly in the slate, but which unexpectedly came down upon a subterranean mound of granite. The student will do well to recollect that it is quite possible for beds to dip directly at and into a mass of granite."[1]

Still larger tracts of granite occur, which cannot be regarded as subsidiary to a single volcano, but seem to have been extensive reservoirs of molten rock which consolidated under a great thickness of superincumbent strata; such tracts often occupy large districts, and evidently extend to a great depth, having been exposed by the removal of the strata which originally covered them.

Granite used frequently to be described as forming the axis of mountain chains, or the nucleus of mountain-masses, and it was taken for granted that the upheaval of the granite tilted and shouldered off the stratified rocks which rested upon it, so that these always dipped away from the granite; the lowest formation resting against it on each side with a regular upward succession as we proceeded from it. The occasional appearance of granite masses in the centre of mountain chains favoured this view, but more careful and extended examination showed that this was an accidental relation.

It is doubtless true that granite is more frequently associated with the older rocks than with the newer, in other words, with the lower than with the higher rocks. This, however, is not to be wondered at, seeing that granite is essentially a deep-seated rock, and that it has risen from beneath the earth's crust; in so doing it must have passed through the lower rocks in order to reach the higher, and

[1] Jukes' "Manual of Geology," third edition, p. 245.

many injections of granite have only penetrated the lower rocks without proceeding further.

There is also a still more cogent reason why granite should occupy this position, viz., that all granite now found at the surface must be there in consequence of vast denudation having taken place, great masses of other rocks having been removed by detrition, together, perhaps, with much of the granite that once existed above the present surface. This denudation of course exposes the lower rocks to view, while parts of the higher rocks that were perhaps equally penetrated by the granite have been removed, the other parts which remain being at a distance from the granite, and showing no signs of such penetration.

The relations of a large mass of granite to the adjoining rocks are generally rather complicated, the boundary line being very irregular, and the granite running out into tongues and bosses as already mentioned. Where the junction of granite with other rocks can be studied over a large area it suggests the arrangement exhibited in the diagram, fig. 161. The molten rock would seem to have forced its way upwards and sideways, eating away support after support of the mass above it, and probably in some cases actually melting them down and absorbing their materials into itself. The pressure from below has caused not only injections of the yet molten rock into the cracks and fissures of the superincumbent mass, but undulations in the general surface of the granite, some parts of the overlying mass being heaved up, and others sinking down into the granite. The upper surface of the granitic mass, on its final consolidation, would thus be an excessively irregular one, with protuberant mounds and deep hollows, while the beds of the superincumbent mass would not be likely to conform at all to this irregular surface, but would often dip directly down on to it, or abut against it in all kinds of ways, and with any amount of inclination.

Fig. 161 may be taken as a diagrammatic illustration of a tract of stratified rock invaded by granite, *G* representing a mass of granite gradually forced upward into the mass of slate which had already been disturbed and tilted in various directions. The horizontal lines, *a b*, *c d*, *e f*, *g h*, indicate successive surfaces of denudation. So long as the

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This, therefore, is a sufficient refutation of the old idea that the intrusion of granite was the cause of elevation, and that the rocks in contact with it were always the lowest and oldest to be found in the country. In the Leinster district it is Silurian or newer rocks which are seen to be altered into gneiss and mica-schist by contact with the granite. "Moreover, in those parts where the granite forms lofty hills, the mica-schist spreads far up on the flank of those hills, and on the very loftiest, such as Lugnaquilla (which is over 3,000 feet above the sea), large patches of mica-schist occur even on the summit, so that the surface exposure of granite is there narrowest and most interrupted." Had the hills been left another 500 or 1,000 feet higher, the granite would apparently have been entirely concealed there by masses of mica-schist stretching completely over it.

"On the other hand, where the granite forms low ground, as above Tullow and Hacketstown, its surface exposure is there by far the widest, and all the central part of it is completely free from patches of mica-schist.

"It is obvious that these differences are the result of the different amount of denudation that has acted on the granite. Where the ground is loftiest we have the nearest approach to the original surface of the granite and its original covering of other rock; where the denudation has cut down deepest, so as to form low ground, there we get deeper into the granite mass, or further from its original surface, to a depth, indeed, to which no mass of mica-schist could extend, unless it were altogether detached from the overlying mass, and enclosed in the granite."[1]

It is therefore almost certain that the whole of Wicklow and Wexford is underlain by a continuous mass of granite with a very irregular surface. The granite district of the Mourne Mountains in county Down presents similar features.[2]

[1] Quoted from Jukes' "Manual of Geology," second edition, p. 318. It should however be stated that the altered rocks cannot be properly called gneiss and mica-schist, though they may be described as *micaceous schists.*

[2] See "Memoirs of the Geol. Survey of Ireland," Sheets 60, 61, 71, 72, one vol., 1881, and Hor. Section 22.

CHAPTER XI.

IGNEOUS ROCKS REGARDED AS ROCK-MASSES.

B. VEINS, DYKES, SILLS, AND LACCOLITES.

CONNECTION of Plutonic and Volcanic Rocks.—From the descriptions given in the preceding chapter the reader will be prepared to accept the remark made long ago by Jukes, that "if we could follow any actual lava-stream to its source within the bowels of the earth, we should in all probability be able to mark in its course every gradation, from pumice or obsidian to actual granite."

The probability of this might be deduced from the similarity in the ultimate chemical composition of Granites, Felsites, Rhyolites, and Obsidians, as shown by the following table of analyses, in which their mean composition is given:—

	Granite.	Q. Felsite.	Rhyolite.	Obsidian.
Silica	72·8	74·27	76·0	71·0
Alumina	15·3	13·12	13·2	13·8
Potash	6·4	4·44	3·1	4·0
Soda	1·4	2·48	4·5	5·2
Lime	0·7	1·17	0·8	1·7
Magnesia	0·9	0·52	0·3	0·6
Oxides of Iron and Manganese	1·7	2·43	1·7	3·7
Loss by Ignition	0·8	1·06	0·6	0·6
	100·0	99·50	100·1	100·0

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ing garnets, while the granite presents the following modifications:—(1) the normal granite passed into a syenitic or hornblendic granite, and a piece taken about ten yards from its contact with the limestone had the following composition:—

Quartz	17·16
Orthoclase	67·18
Hornblende	15·40
	99·74

(2) the veins proceeding from this hornblendic granite, and penetrating the limestone, passed into a kind of basic diorite or corsite consisting of—

Anorthite	85·84
Hornblende	14·16
	100·00

Comparing the last two rocks we see "that the quantity of hornblende remains almost unaltered, and that the effect of the addition of limestone to the melted granite has been to convert the quartz and orthoclase into anorthite. In this operation the alkalies of the orthoclase have disappeared; the lime being a more fixed base at high temperatures has altogether displaced the alkalies."[1] It may also be observed that the corsite contains 24 per cent. less silica than the hornblendic granite.

Segregation Veins.—Veins of a compact felsitic character are sometimes to be found in the granite itself, and contrast strongly with the surrounding coarsely crystalline and highly micaceous rock. Instances occur at Killiney, near Dublin, where, in veins about three feet wide, the general mass of the rock is ordinary coarse-grained, micaceous granite, "but parts of them suddenly change into fine-grained, almost compact rock (eurite), in transverse bands of irregular shape. These bands look as if they were subsequent veins injected into the other granite; but as they are strictly confined to the granite veins, and do not penetrate the adjacent slates, it is impossible to attri-

[1] "Quart. Journ. Geol. Soc.," vol. xii. pp. 192-198.

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proportion of potash. This is explained by Mr. Teall as the effect of progressive crystallization, a portion of the mass consolidating first, and being of a comparatively basic composition with low silicated felspars, while the remaining portion formed a sort of mother-liquor with a more acid composition.

Thus the syenitic rock of Penmaen Mawr, near Conway, has a micrographic matrix of quartz and orthoclase, in which are scattered previously formed crystals of lime and soda felspars. In the mass occur segregation veins, which Mr. Teall describes as perfect examples of micro-pegmatite with crystals of augite, and he observes that "on comparing the veins with the rock it will be noted that they consist of the minerals which formed last, namely, augite, orthoclase, and quartz. . . . They are composed of the mother-liquor left after the separation of the more basic compounds."[1] Thus they appear to be portions of the magma in which silica was concentrated, but maintained in a liquid condition by the presence of steam and water-gas under pressure, and were injected as veins into that portion of the mass which had previously consolidated.

This view finds confirmation in the fact mentioned on p. 340, that when analyses have been made of the crystalline and glassy portions of the same rock, the glassy base always contains more silica than the crystals, and appears also to hold more combined water.

Dykes and Elvans.—A dyke is a wall-like mass of igneous rock which has been intruded along the line of a more or less vertical crack or fissure. Dykes have already been mentioned in Part I., Chapter II., but those described in that connection were chiefly the smaller dykes which intersect the volcanic cone itself, and not the more deep-seated dykes which traverse the underlying rocks. When such dykes are exposed to view by subsequent denudation, the baked or partially fused condition of the rocks which form the sides of the lava-filled fissure clearly indicate the igneous character of the intruded material. The extent to which the adjoining rocks are thus metamorphosed, varies from a few inches to several feet.

[1] Teall, "British Petrography," p. 274.

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a dyke coinciding with a fault and thinning out upward while the faulted fissure continues, is mentioned in Lebour's "Geology of Northumberland" (p. 48).

One of the most remarkable examples of a dyke is that known as the Cleveland dyke, which runs from the Yorkshire coast south of Whitby for a distance of about sixty miles in a north-west direction to Cockfield Fell in Durham. This dyke forms a nearly vertical wall of basalt 50 or 60 feet thick, cutting through all the other rocks which it meets with, and baking them for a distance of some yards from its sides.

We have no means of knowing how far such dykes extend downward into the earth, but if we could follow them far enough we should probably find that they proceeded

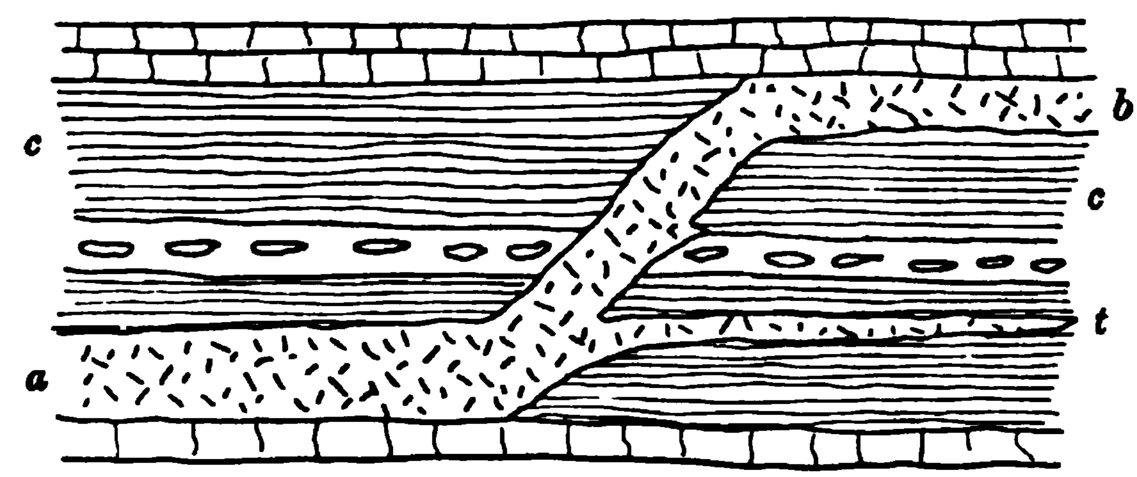

Fig. 166. Sheet of Igneous Rock, *a b*, traversing Shales, *c*, and sending off a Tongue, *t*.

from some large intrusive mass of diorite or syenite, and that they exhibited every gradation from the characters of a Volcanic to those of a Plutonic rock.

Intrusive Sheets, or Sills.—When, instead of filling a more or less vertical fissure, the igneous rock has been intruded between the planes of stratification, it is called a sill. The rocks above and below a sill are, of course, baked and altered just in the same way as the rocks on each side of a vertical dyke.

Intrusive sheets of Diabase have been traced for many miles in the rocks of North Wales, running regularly between two beds, as if they were interbedded with them, till at length they were found to cut obliquely up or down, and continue their course between other beds (see fig. 166).

Mr. Harker observes that "these sheets have everywhere partaken of the contortions of the strata among which they lie, and it is even possible in the case of the larger intrusions to trace the manner in which the folding has been modified by the presence of these stubborn masses of rock among less resisting materials. It may be asserted with some confidence that the latest of the basic sheets were injected almost at the time when the plication of the strata was in progress, so that their form and distribution are partly determined by the folds.[1] Occasionally they thicken out into lenticular masses, but still keep to the same stratigraphical horizon.

The great "Whin sill" is a sheet of enstatite-dolerite, thrust into and between the Lower Carboniferous strata, and its outcrop extends for a distance of about 80 miles through Cumberland and Northumberland, and an inlier

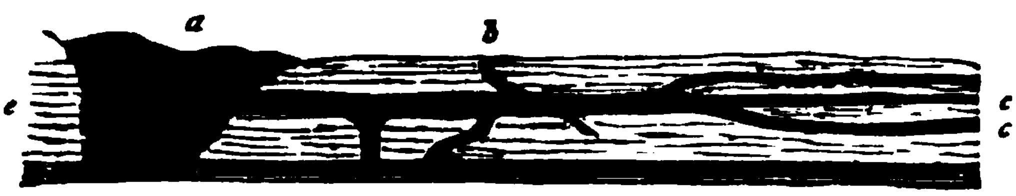

Fig. 167. Dyke and Sheet of Basalt, Trotternish, Skye.

of it occurs in Teesdale, so that it must have a very wide subterranean extent. Its average thickness is from 80 to 100 feet.

The island of Skye has already been mentioned as exhibiting many examples of vertical dykes, and associated with these there are equally interesting and instructive cases of intruded sheets. Fig. 167 is copied from a sketch by Dr. Macculloch, and shows a large dyke-like mass of basalt, *a*, piercing the sandstones, *e*, and giving off a thick horizontal sheet, which splits up into three smaller sheets or veins (*c c c*); other dykes and veins run into or from this sheet, both upwards and downwards.

The extent and thickness of intrusive sheets is sometimes very considerable; that of the "Whin sill" has already been mentioned; in South Staffordshire a large sheet of dolerite, varying in thickness from 20 to 60 feet,

[1] "The Bala Volcanic Series of Carnarvon," p. 76.

was found to spread over an area of at least twenty square miles; in one part of the district it lies at a certain depth below the bottom coal, but in another part it passes upwards through that coal and spreads out over it, in some places even sending up dykes and protuberant bosses into still higher measures.

In such cases as these we may suppose that having been forced up through previously-formed fissures to a certain height, the molten rock then met with such resistance above, that it was as easy for it to lift the overlying beds as to break through them (see fig. 167). The planes of stratification would then become those of least resistance, and the molten stream would be injected along those which yielded the most readily, thinning and swelling out according to the varying pressures which were encountered in its course.

Laccolites.—The explanation just given leads us to the consideration of the still more massive intrusions, forming huge lenticular masses of felspathic or trachytic rock, to which Mr. G. K. Gilbert has given the name of *laccolites*, or stone-cisterns.[1] These appear to consist of the less fluid acid lavas, which do not flow so rapidly (see p. 26), and would not be able to make their way between the planes of stratification so easily as the more fluid basaltic lavas. Such intrusions, therefore, would excrcise still greater upward pressure, and could not fail to lift the overlying beds to a greater extent than the doleritic intrusions, while the accumulated weight will doubtless also depress the underlying rocks to some extent (see fig. 168). The intrusion will eventually take the form of a vast lenticular mass or reservoir of igneous rock.

Laccolites are usually drawn with a vertical pipe, or feeder, beneath them, but it seems probable that in many cases the feeder was at one end of the lenticular mass. When they occur in a series of inclined and flexured strata their outcrops will form oval or lenticular patches, the longer axes of which will always coincide with the strike of the beds in which they lie. Mr. Harker observes that "this elongated form of outcrop and

1 "Geology of the Henry Mountains," U.S. Geol. Survey, Washington, 1877.

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[illegible] p. 43.

It has frequently happened that the streams of lava which were poured out of a volcano on to the floor of a neighbouring sea or lake have been preserved, while the volcano itself has been destroyed. The volcano may have been situated near the sea-shore, or it may have been a volcanic island, or it may have been entirely submarine, and it is the accident of its having been adjacent to an area of deposition that has led to the preservation of its lavas.

Each flow or coulée of lava has been covered up by the deposits which were accumulating in the adjacent lake or sea, and when the whole area has been upheaved and dissected by the scalpel of aqueous erosion, the lava-flows are seen to be *interbedded* or interstratified with the sedimentary deposits. Their very nature and mode of origin, therefore, limits them to this one form or mode of occurrence, and all such interstratified masses may consequently be described as *sheets*. Further, it is evident that they and the sedimentary beds with which they are associated must constitute one consecutive series, and that in this sense the sheets of igneous rock are contemporaneous with the beds of stratified rock. With them are frequently associated deposits of ash or tuff, the material being sometimes fine, sometimes coarse or conglomeratic, and often compacted and indurated into a hard and rough rock.

Proofs of Interbedding.—It is particularly important that the observer should be able to decide whether any sheet of igneous rock he may meet with is interbedded or intrusive; whether, in fact, it is to be regarded as contemporaneous with the rocks among which it lies, or as having been intruded between them at some subsequent time, for upon this determination depends the geological date which is assigned to the rock in question. It will therefore be desirable in the first place to examine the signs and circumstances which serve to distinguish interbedded from intrusive sheets of lava or trap. These are,

1. The slaggy or vesicular character of the upper and lower surfaces of the sheet.
2. The unaltered character of the overlying beds and their general relations to the surface on which they rest.
3. The association of stratified ashes or tuffs.

1. In the description of lava-streams given on p. 26, it was stated that their upper surface or crust was sometimes rendered slaggy and ropy by the motion of the current, and in other cases it became vesicular and scoriaceous from the escape of the contained gases. The surface of all lava-streams presents one of these two conditions in a greater or less degree, but intrusive sheets which have solidified under the pressure of the overlying beds do not exhibit these appearances. The under-surface of a lava-stream is also very frequently full of vesicles, so that it is then vesicular both at the top and bottom; subsequent infiltrations may convert these vesicles into amygdaloids, but this only renders them more conspicuous. The cavities are often drawn out and elongated in the direction of the flow, so that by this means it is sometimes possible to ascertain the direction from which the amygdaloidal rock has come.

Fig. 169. Lava resting on Sandstone.

2. It is obvious that the beds overlying a contemporaneous sheet cannot be altered by it, because they were not there when the rock was poured out as a stream of lava. An interbedded sheet, therefore, only alters and bakes the beds below, while an intrusive sheet affects those above as well as those below. The absence or presence of intrusive tongues or veins proceeding from the sheet is likewise a criterion, their presence at once indicating its intrusive nature. Farther, the stratification of the beds overlying an interbedded sheet generally affords evidence of their having been deposited upon the irregular surface of the trap, as indicated in fig. 169. The stratified rock fills up any hollows or cracks which may exist in its surface, and often encloses small pebbles or blocks which have been broken off from it.

3. The presence of stratified tuffs also raises the presumption that the associated sheets of lava are interbedded

and contemporaneous, though it does not absolutely prove this to be the case, for as we have seen, masses of tuff and agglomerate frequently fill up volcanic necks, and are then associated with the intrusive dykes which proceed from it. Still, if the sheets of trap are clearly interstratified with beds of "ash," and if the ash-beds do not exhibit any signs of baking or alteration where they are in contact with the lava, then it becomes almost certain that the trap is contemporaneous.

Consecutive Flows.—Occasionally a single flow or sheet of trap is met with, and sometimes several such single flows are interbedded with a series of stratified rocks; more frequently, however, what appears to be one massive sheet is in reality made up of several distinct lava-flows poured out at separate intervals from the volcanic vent. The independence of the flows is sometimes indicated by differences of texture, one being compact, another porphyritic, another columnar, and so on; even when all are similar in character, there are sometimes zones of vesicular or amygdaloidal rock, formed by the union of the upper and lower surfaces of two flows, which mark the lines of division between them. Lastly, the fact that such a mass is really made up of successive flows is often clearly demonstrated, when their outcrops are traced for some distance, by the intercalation of other beds between some of the component sheets. Such an occurrence proves that the lava currents invaded an area where deposition was going on, and that sufficient time elapsed for material to be deposited on the surface of the first sheet before it was overflowed by the second.

An excellent instance in which consecutive flows of doleritic lava are interstratified with shales and sandstones belonging to the Coal-measure series occurs in the Borrowstounness coalfield, Edinburgh. The middle part of this series is described as consisting of the following alternations of igneous and aqueous rocks:—

	Feet.
Shales and sandstones	—
Dolerite	20
Shale and sandstone	6
Dolerite in several sheets, with partings of shale and sandstone in places.	265

	Feet.
Shale, coal, and sandstone	30
Dolerite in several sheets	110
Shales and sandstones	25
The "red coal" seam	3
Dolerite	4½
Sandstone	16

In one shaft the thickest compound mass of dolerite was found to be separated into two portions by the intercalation of 30 feet of shale and sandstone.[1]

Such intercalations and alternations of lava-flows and aqueous rocks are frequent wherever extensive eruptions have taken place, and the whole groups of strata thus formed have, of course, partaken in all the accidents of tilting, flexure, and fracture, by which the district has been affected since the time of their formation.

Instances of Interbedded Lavas and Ashes.—1. *North Wales.*—The ancient volcanoes of Carnarvonshire have been mentioned on p. 473, and two of them, Y-foel-fras and Mynydd Mawr, have been described. Writing of this district Sir A. Geikie remarks, "So great has been the denudation of the region that the pile of lavas and tuffs which accumulated around and above these orifices has been entirely swept away. No trace of any portion of that pile has survived to the west of the line of bosses; while to the east, owing to curvature and subsequent denudation, the rocks have been dissected from top to bottom, until almost every phase of the volcanic activity is revealed."[2]

The thickness of volcanic material exposed on Snowdon alone is estimated at over 3,000 feet, and according to the most recent observations, they consist of the following members:—

	Feet.
Grey amygdaloidal lavas with a sheet of felsite .	150
Thick beds of tuff with sheets of felsite	1,200
Porphyritic felsites, many of the sheets showing slaggy surfaces	1,700

"But this includes only the higher part of the whole volcanic group. Below it come the lavas of Y-Glyder Fach,

[1] "Geology of Edinburgh," Mem. Geol. Survey, p. 63.
[2] "Pres. Address to Geol. Soc.," 1891, p. 83.

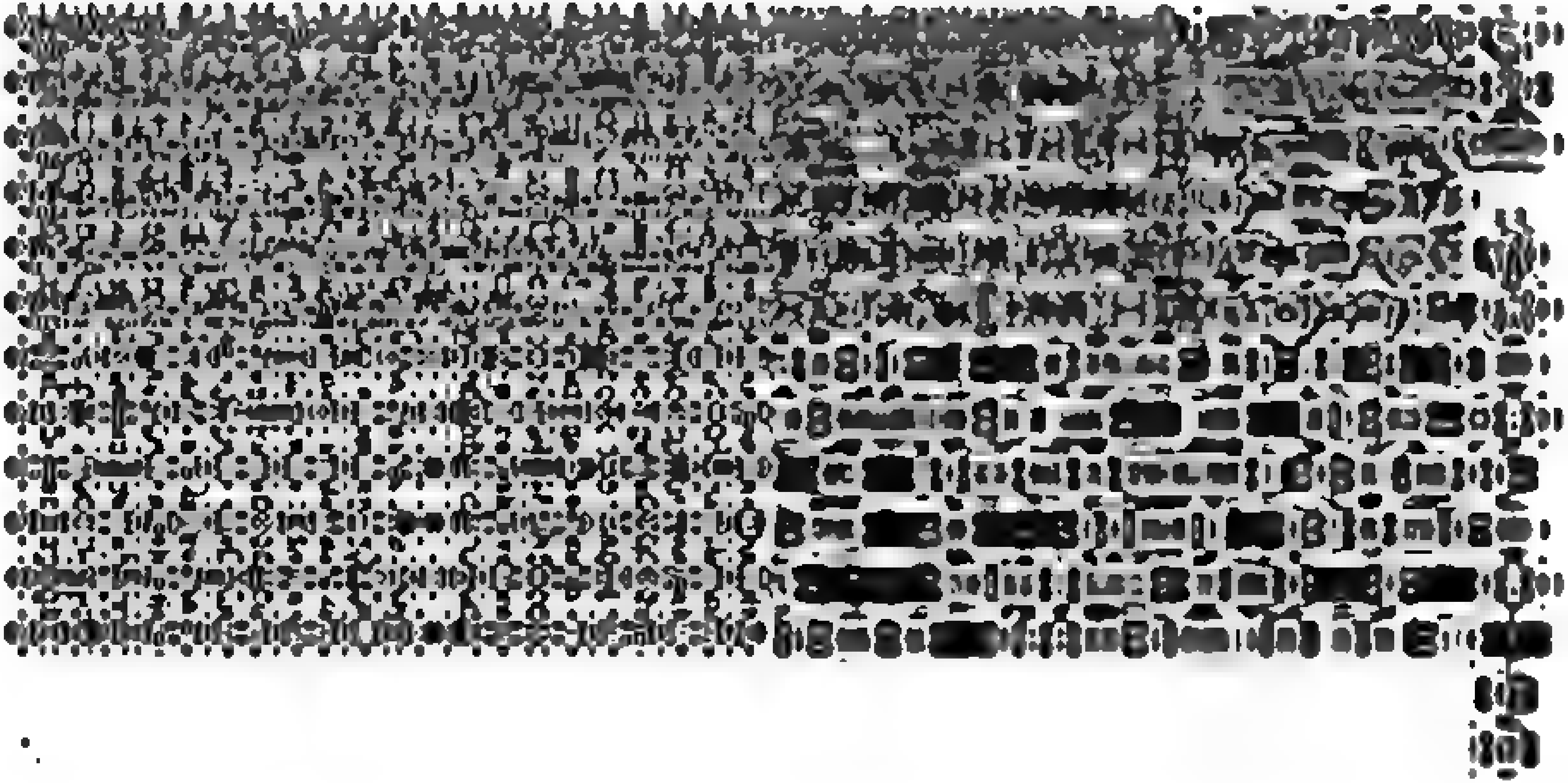
which according to the Survey measurements[1] are about 1,500 feet thick, while still lower lie the ancient coulées of Carnedd Davydd and those that run north from the vent of Yfoel-fras, which must reach a united thickness of many hundred feet. We can thus hardly put the total depth of volcanic material at a maximum of less than 6,000 to 8,000 feet. The pile is, of course, thickest round the vents of discharge, so that no measurement, however carefully made, at one locality, would be found to hold good for more than a short distance." (Geikie, *loc. cit.*, p. 83.)

From the volcanic centres the lava-flows thin in all directions, becoming intercalated with beds of shale and sandstone, and finally dying out altogether. The same is the case with the ash-beds, which near the volcanic centre are extremely hard and compact, and consist entirely of the débris of slaggy and scoriaceous lavas, so that they sometimes resemble the decomposed portions of the felstones; but as they are traced from the central area they become thinner, more regularly bedded, and more obviously mechanical, the ashy and cindery materials become mixed with an increasing proportion of sandy, clayey, or calcareous sediment, and they finally pass into pure sandstones, shales, or limestones.

Remarking on the frequency of slagginess and flow structure in the lower felsitic lavas of Snowdon, Sir A. Geikie points out that careful observations on this structure would often indicate the direction from which the lavas came. He instances one of the lowest sheets which forms a line of picturesque crags on the slope facing Llanberis. "The general push indicated by [the curled and overfolded layers of the lava] points to a movement from the westward. Turning round from the crags and looking toward the west, we see before us on the other side of the deep vale of Llyn Cwellyn, at a distance of little more than three miles, the great dome-shaped Mynydd Mawr, which, there is reason to believe, marks one of the orifices of eruption" (*loc. cit.*, p. 85).

2. *The Limerick Basin.*—Ireland presents us with a good example of interstratified aqueous and igneous rocks in

[1] See Sir A. Ramsay's "Geology of North Wales," Mem. Geol. Survey.



Limestone. a b a c a c a c a c

Fig. 170. Section through part of the Volcanic Series of Limerick (after Hull).
a, Beds of tuff and ash. b, Basalt (possibly intrusive). c, Sheets of porphyrite.

parallel laminæ, the coarse and fine layers often alternating in regular bands about half-an-inch in thickness.[1]

Some of the sheets of felstone, 800 or 1,000 feet thick, are found, when followed along their strike, to split up and let in alternations of beds of ash and beds of limestone, showing that the greater uninterrupted masses were in reality formed by successive flows of molten rock at the bottom of the sea, and that, where each of these flows terminated or became thin, accumulations of ash or limestone took place on the sea-bottom in the intervals between the outpouring of one flow and that of the next, so as to cause these interstratifications. Pallas Hill is a conspicuous example of this occurrence.

On the south side of this volcanic area there are five intrusive bosses of felspathic rock rising up through the lower limestone, and another boss at about the same distance on the the north side of the basin. These look like some of the volcanic foci from which the lavas were derived, the old roots, as it were, of the submarine lava flows, exposed to view by the denudation of the limestones and traps that once covered them. Other foci or intrusive masses are doubtless concealed beneath the existing beds of trap in the central parts of the basin.

Professor Hull more recently has distinguished two epochs of eruption in the Limerick area, the first being an extrusion of felspathic lavas and ashes, while the second, which occurred after a considerable interval, gave birth to flows of augitic lava (basalt, etc.) The sect. (fig. 170), copied by permission from Prof. Hull's "Physical Geology of Ireland" illustrates the succession of materials erupted during the earlier outburst.

3. *Scotland.*—The country which lies on either side of the Firth of Forth was anciently the scene of great volcanic activity. Arthur's Seat in Edinburgh and Largo Law in Fife are excellent instances of denuded volcanic piles; the numerous necks of Fifeshire have already been mentioned, and the behaviour of interbedded and intrusive sheets of

[1] See the Explanations of Sheets 143, 144, 153, 154 of the Geological Survey of Ireland, and Jukes' "Manual of Geology," second edition, p. 325.

lava can be studied in the cliff sections along the coast.[1] Most of these eruptions took place towards the end of the Carboniferous period, but evidence of an earlier series of volcanic explosions are to be found in the ranges of the Sidlaw, Ochil, and Pentland Hills. "All these prominent ridges," says Sir A. Geikie,[2] "are formed mainly of volcanic materials belonging to the period of the Lower Old Red Sandstone. Their general characters—beds of lava (porphyrite, etc.) with sheets of tuff and interstratified sandstones, shales, and conglomerates—leave no doubt whatever as to their having been truly erupted to the surface during that geological period.

Basaltic Plateaux.—It has long been assumed that all erupted basaltic sheets were remnants of lava-flows which had once been connected with true volcanic cones. Baron Richthofen had indeed pointed out so long ago as 1868, that on the Pacific slope of the Rocky Mountains there is evidence of the emission of vast floods of lava without the formation of cones and craters, and he stated his belief that these eruptions had proceeded from great fissures out of which the lava had poured in a continuous stream. This theory was energetically opposed by Mr. Poulett Scrope, who demonstrated that the extensive plateaux of basalt in Auvergne were only separated from the cones with which they had originally been connected in consequence of the great erosion to which that country had been subsequently exposed. He argued that the apparent isolation of other plateaux was merely owing to the total destruction of the volcanoes from which they had been emitted (see Plate, fig. III).

Subsequent observations, however, have tended to confirm the probability of Richthofen's views; the extent of these American lava-floods has been found to be enormous, and it is estimated that in the States of Oregon, Idaho, Nevada, and Northern California they cover an area of 200,000 square miles. The date of their emission is comparatively recent; they have been poured forth over the bottoms of the present valleys, and the only natural sec-

[1] Consult Sir A. Geikie on the "Volcanic Rocks of the Basin of the Forth, Trans. Roy. Soc. Edin.," xxix. p. 437.

[2] "Trans. Geol. Soc. Edin.," vol. ii. pt. iii.

tions of them are those in the gorges or cañons which the present rivers have been able to erode out of the vast plain of basalt.

Sir A. Geikie thus describes one of these enormous lava fields[1]:—"We had been riding for two days over fields of basalt among the valleys, and [at last] emerged from the mountains upon the great sea of black lava which seems to stretch illimitably westwards. It was as if the great plain had been filled with molten rock which had kept its level, and wound in and out along the bays and promontories of the mountain slopes as a sheet of water would have done. . . . . I looked round in vain for any central cone from which this great sea of basalt could have flowed. It assuredly had not come from the adjacent mountains, which consisted of older and very different lavas round the worn flanks of which the basalt had eddied. . . . I became convinced that all volcanic phenomena are not to be explained by the ordinary conception of volcanoes, but that there is another and grander type of volcanic action where the molten rock has risen in many fissures, and has welled forth so as to flood the lower ground with successive horizontal sheets of basalt."

He suggests that the similar sheets and dykes of basalt which occur in the north of Ireland and west of Scotland, and the enormous dykes which are so frequent throughout Scotland and northern England, are all manifestations of a grand series of fissure eruptions comparable to those in North America, but belonging to an earlier geological period. In support of this conclusion he appeals to the wide extension and horizontality of the basalt sheets, the absence or paucity of interstratified tuffs, and finally thei apparent connection with a series of lava-filled fissures, some of which are no less than 200 miles distant from them.

It should be mentioned, however, that the cogency of this evidence is disputed by Prof. Judd, and that contemporaneous volcanoes from which the lavas might have come certainly existed both in Scotland and Ireland.

That portion of the great lava-flood which is isolated in the north-east of Ireland covers almost the whole of county

[1] "Geological Sketches," by A. Geikie, p. 278.

Antrim with a mass which is in some places 900 feet thick; it is 50 miles long by 30 wide, or about 1,200 square miles in area. The basalt mass consists of numerous sheets or flows, some of which are quite amorphous, either compact or amygdaloidal, while others are beautifully columnar; one of the columnar sheets dipping gradually into the sea on the north coast is known as the Giant's Causeway.

Similar extensive plateaux of basalt occur in other parts of the world, in Abyssinia, western India, and Victoria, and probably mark the sites of some of the great fissure-eruptions which have taken place at different times in the history of the world. In their recent *résumé* of the geology of India, Messrs. Blandford and Medlicott describe the persistent horizontality of the great basalt sheets which form the plateaux of the Deccan, the absence of any trace of associated volcanic cones, and the abundance of dykes which traverse the underlying platform of older rocks, where these emerge from beneath the basalt-covered area.

CHAPTER XII.

METAMORPHIC ROCKS.

THE consideration of these rocks has been left till this stage because the peculiar structures which they exhibit could not be properly explained to the student until he had been made acquainted with the manner in which the unaltered rocks, both of aqueous and igneous origin, occur in the earth's crust, and had obtained some idea of the results caused by the intrusion of igneous among aqueous rocks, and by the earth-pressures to which both have been subjected from time to time.

Metamorphic rocks may be broadly defined as those which, after their first consolidation, have been so altered that their internal structure and their physical characters are different from what they originally possessed. This change may be molecular, or atomic, or may be chiefly the result of mechanical stress or pressure; thus: (1) The molecular arrangement and physical character of the rock may be altered without much mineral change; for this kind of metamorphism Dr. Irving has proposed the name of *metatropy*. (2) The original mineral particles of the rock-mass may have been rearranged by mechanical stress; for this kind of change Dr. Irving has suggested the term *metataxis*.[1] (3) The mineral components of the rock may be recombined into minerals of different chemical composition; for this Prof. Bonney has suggested the excellent term *metacrasis*.[2]

A simple case of metatropy is that of a limestone which

[1] "Metamorphism of Rocks," Longmans, 1889, p. 5.
[2] "President's Add. Geol. Soc.," 1886, p. 31.

has been converted into a crystalline-granular marble by the heat of intrusive igneous rock, its optical and physical characters being changed while its chemical composition remains nearly the same.

A simple case of metataxis is that in which a rock has been so compressed that its component particles are all elongated in one direction, and the rock has consequently a tendency to split in that direction. A rock which has this structure and splits into thin layers which are not those of original deposition is said to be *cleaved*, and the structure is called *cleavage*, or slaty-cleavage, from its leading to the production of slates.

Metacrasis may be sometimes of a simple character, either paramorphic, as in the change of a dolerite into an epidiorite by the conversion of augite into hornblende, or pseudomorphic, as in the production of serpentine from an olivine rock; but it is often a more complicated process, as in the combination of the disintegrated mineral particles of a sedimentary rock and their recrystallization into fresh minerals. It must be remembered that clays and clayey sandstones consist of minute particles of kaolin, mica, and quartz-sand, derived from the disintegration of granitic rocks, and that they usually contain small amounts of iron oxide, lime, and alkali; so that under the combined influence of pressure and superheated water-vapour these particles might be recombined into crystals of felspar, mica, and quartz, like those from which the ingredients of the clay were originally derived.

When in the course of such recrystallization the minerals have arranged themselves in thin lenticular layers which are all elongated in the same direction, so that the rock splits along them, the rock is said to be *foliated* (from *folium*, a leaf) and the structure is termed *foliation*. This term was originally proposed by Professor Sedgwick, and was defined by him as "a separation into layers of different mineral composition," while cleavage means only "a tendency to split in a mass of the same composition." Foliation is a chemical change effected under the concomitant influence of great pressure, and the structure may be produced in crystalline igneous rocks as well as in clastic sedimentary rocks. A kind of foliation may also be pro-

duced in an igneous rock by fluxional movements in the mass before it was completely solidified and still in a viscid condition.

It must be borne in mind that many masses of igneous rock may be included in a region that is being compressed and metamorphosed, and that the alterations effected in the igneous and aqueous rocks will tend to make them resemble one another much more than they did in their unaltered states, so that it may sometimes be difficult to say whether a given foliated rock was originally an aqueous or an igneous formation.

There are certain special structures exhibited by metamorphic rocks which must be defined before the rocks are described. The following are the most important.

When the rock consists of small even-sized crystals of quartz and felspar it is said to be *granulitic*, and there may be a granulitic ground-mass with lenticular lumps or *phacoids* consisting of larger crystals.

When a rock has been crushed so that it consists of small lenticular or granular components separated by a fine-grained material, which appears as a "flowing tissue of opaque fibres and strings" (Lapworth), as if the rock had been partially ground to dust between millstones, it is said to have a *mylonitic* structure, and is sometimes called a *mylonite*.

When the foliated materials are arranged around some hard crystal, so that this, with the curving layers above and below it, resembles an eye, we have what is called the "eye structure" (*augen*-structure).

When the matrix looks as if it were flowing round and through the larger components, the rock is called, by the Germans, *flaserig*, or veiny, because it always has a veiny, banded appearance to the eye. This arrangement is often spoken of as *flaser-structure*, and it may exist apart from eye-structure in a rock.

The following are brief descriptions of the different kinds of metamorphic rocks which are generally recognized. Among the less altered forms, those of aqueous and igneous origin can be easily distinguished, but among the more altered rocks this becomes a difficult matter.

A. *Rocks without Foliation.*

Under this head are included (1) sedimentary rocks which have been altered by heat only (baked rocks), or by pressure which has not been carried beyond the degree necessary to produce cleavage; (2) igneous rocks which have undergone simple paramorphic changes.

1. *Altered Sedimentary Rocks.*

Quartzite.—This is an altered sandstone, and has been defined as a rock consisting of quartz-grains cemented together by crystalline quartz, the crystals of which are commonly arranged in crystalline continuity with the quartz of the original sand-grains. It is thus distinguished from sandstones with an infiltrated siliceous cement, which is always either opaline or chalcedonic. It is probable that the secondary quartz in quartzite has been derived from the sand-grains by the solvent action of hot vapour or steam, for it must be remembered that every intrusion of igneous rock must generate such vapour out of the interstitial water in the surrounding stratified rock.

Halleflintas are compact siliceous rocks, not unlike felstones in general aspect. They may have been formed from fine-grained felspathic sandstones by induration and partial fusion, but some may have resulted from the alteration of fine felspathic tuff (trachytic dust).

Porcellanite and *Argillite* are baked and indurated clays, appearing as close-grained flinty or jaspery rocks, generally of a greenish, greyish, or reddish colour. *Lydian stone* is a black or dark-brown rock of similar texture, resulting from the metatropic alteration of a carbonaceous clay or shale; it often contains crystalline grains of quartz, and must then have been either a sandy shale or a siliceous clay like fire-clay.

Marble is a limestone altered by heat and pressure into a crystalline rock consisting of closely-packed crystals of calcite. The limestone may have been originally earthy, shelly, or partly crystalline; by *marmorosis* (as the making of marble is termed) all the carbonate of lime is recomposed

into crystalline grains of calcite, which are interlocked one with another.

By heating chalk and limestone in closed tubes, to prevent the escape of carbonic acid gas, Sir James Hall succeeded in converting them into hard crystalline marble, and in another experiment he actually fused the substance, which then acted powerfully upon other rocks. In Nature, heated water under pressure of superincumbent rocks has probably played a prominent part in the production of marble.

The chalk of the north-east of Ireland, where penetrated by dykes of basalt, is altered in some places into a hard grey semi-crystalline limestone, and in others into a white coarsely-crystalline marble. In many marbles certain silicates, such as idocrase, garnet, and green augite have been developed, and in some mica and graphite (pure carbon) has been found.

Ophicalcite is the name for a group of rocks which requires further investigation; it may be defined as consisting of crystalline calcite or dolomite, veined and permeated with serpentine. Some ophicalcites, like the Galway serpentine or Connemara marble, certainly seem to be metamorphic limestones in which lime-silicates have been formed, and subsequently altered into serpentine; but others may be only broken serpentines recemented by infiltrated calcite; and others again may possibly be due (as suggested by Professor G. Cole) to the complete decomposition of an igneous rock consisting of anorthite and olivine.

Lime-silicate rock (*Kalkhornfels*).—Limestones in contact with large masses of igneous rock have undergone a remarkable degree of metamorphism, resulting in complete paramorphic change. The carbonic acid seems to have been gradually driven off by the heat, and its place has been taken by silicic acid, with which the lime has combined to form various lime silicates; so that the rock has been changed from a calcareous to a calcareo-siliceous one, such as the Germans call *Kalkhornfels*, or calcareous hornstone. It often happens that a limestone contains some argillaceous matter which enables an alumino-calcareous silicate, such as augite, to be formed.[1]

[1] See Harker and Marr on Shap-Granite, "Quart. Journ. Geol. Soc.," vol. xlvii. p. 314.

The gradual development of the silicates at the expense of the calcite is often traceable where a limestone can be followed along its strike till it abuts on the igneous rock. At a certain distance from the latter the limestone is only a marble with a few small scattered crystals of some lime-silicate; nearer to it these crystals are larger and more numerous; nearer still they form the greater part of the rock, only a few patches of calcite being left; finally, within 300 yards of the igneous mass, the rock consists entirely of silicates, and becomes either a light brown idocrase-garnet rock, or a pale bluish or greenish grey hornstone, consisting chiefly of tremolite or pyroxene. These changes are exhibited by the Coniston limestone near its contact with the Shap-Granite (Westmoreland).[1]

Slate is a fine-grained argillaceous rock in which cleavage has been developed, so that the rock splits into thin parallel layers, which are more or less oblique to the planes of bedding. Slates are generally cleaved clays or shales, but some have been formed from fine volcanic tuff. The original lamination is generally imperceptible, but in some slates it is marked by bands of different colour, and these are termed the *stripe* of the slate. When tracts of slate are examined in the field the original bedding is often indicated by alternating bands of finer and coarser slate, which represent the beds of different texture in the originally stratified rock.

Phyllite is a slate in which some secondary mica has been developed, this mica appearing in minute silvery flakes along the planes of cleavage, and giving a peculiar glossy aspect to the slate. In addition to this, phyllites frequently exhibit a minute wrinkling, which may be regarded as an incipient stage of schistosity or foliation. In the neighbourhood of igneous masses slates often show signs of further chemical metamorphism in the occurrence of sporadic crystals of chiastolite, andalusite, garnet, and other silicates of alumina.

[1] See Messrs. Harker and Marr's paper, "Quart. Journ. Geol. Soc.," vol. xlvii. p. 310.

2. *Altered Igneous Rocks.*

Altered Granites.—Along the borders of a granitic mass accessory minerals are often developed, due probably to the subsequent upward passage of steam and hot spring-waters. One of the commonest of such minerals is Schorl or Tourmaline, which seems to be developed at the expense of the mica or felspar. The granite is then termed *schorlaceous.* When the rock is entirely composed of quartz and schorl without felspar it is called *Schorl-rock.* A beautiful variety of schorlaceous granite, where crystals of red orthoclase are scattered through a matrix of quartz and schorl, occurs at Luxullian in Cornwall, and is known as *Luxulianite.*

Sometimes chlorite, cassiterite (tin-ore), and pyrites are added to the constituents of granite, forming a blackish rock, which is called *Zwitter.* A rock consisting of quartz and lepidolite, with scattered crystals of topaz, developed at the expense of the felspar, is called *Greissen;* it occurs in Saxony, but is not of common occurrence.

Altered Gabbros and Dolerites.—The felspar of these rocks has often been converted into a hard white mineral, which was formerly called *Saussurite;* in section it is dull and opaque, and it is now known to be only partially decomposed plagioclase felspar. The pyroxene of Gabbro is also altered into hornblende, often the bright green variety called Smaragdite, so that both rocks are then composed of saussuritic felspar and hornblende; for such rocks the name *Euphotide* is often used. The felspar of a Diorite may also be altered in the same way. By similar changes, the pyroxene being partially or wholly altered into hornblende or actinolite, dolerites pass into the condition known as *Epidiorite.* If chlorite is developed the rock is called a *Diabase.* This change is probably chiefly due to alteration by water, and some calcite is generally present. A Diabase is generally greenish, or dull grey.

Altered Basalts.—These are generally known as *Melaphyres,* being dark green or black rocks. The olivine, when present, is converted into serpentine; epidote and calcite arise from the decomposition of the basic sili-

cates, and zeolites are frequently formed in the vesicles and cavities.

By contact with coal or carbonaceous shale basalt and dolerite have often been changed into what is called *White-trap*, a white, pale green, or pink rock, of which about a fourth part consists of the carbonates of lime and iron, with 10 or 11 per cent. of water. This alteration is probably due to the extraction of organic acids from the carbonaceous matter and their solution in the heated interstitial water of the rock, and the reaction of this solution on the igneous rock.

Altered Andesite.—Andesites which have been altered by solfataric action contain chloritic minerals developed from the hornblende and mica, and very often epidote and iron pyrites. For such rocks Professor Judd has revived the name of *Propylite.*

Altered Peridotites.—These form the rock so well known by the name of *Serpentine*, of which that of the Lizard, in Cornwall, forms an excellent type—a compact, massive rock, mottled with various tints of dull brown, red, and green, and containing lustrous crystals of a certain variety of enstatite. Chemically they consist mainly of hydrated silicate of magnesia and oxides of iron.

B. *The Foliated Rocks.*

These owe their structure partly to chemical change and partly to deformation by forcible compression, as will be shown hereafter, the one action resulting in the formation of new minerals, and the other in their arrangement along certain planes in the rock-mass. Sometimes they show a wrinkled and crumpled structure, which has probably been produced by extreme pressure acting on a mass in a plastic or semi-plastic condition. As it is not always possible to say whether a given foliated rock was originally an igneous or a sedimentary rock, no attempt is here made to distinguish between them. Some are certainly altered Sediments, and some as certainly altered Igneous rocks.

Schists.—These are the foliated rocks resulting from

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foliation. *Sericite-schist* is a rock with light green, silvery mica.

Quartz-schist is one in which quartz particles are more abundant than those of mica. There are, of course, all varieties, from a quartzose mica-schist, where the proportions of quartz and mica are nearly equal (fig. 171), to a rock that is almost a quartzite; but the name of quartz-schist is generally applied to rocks which consist mainly of quartz, with just enough mica to give the rock a schistose aspect, and to cause it to split along planes of foliation.

Spotted schist (Fruchtschiefer of the Germans) is a micaceous schist full of dark-brown or black spots and patches, most of which are embryo crystals of aluminous silicates, not sufficiently developed to show regular faces or specific characters. Recognizable garnets and cubes of iron pyrites, however, sometimes occur, and both are common in all schists. The black spots often consist of particles of graphite.

Andalusite-schist, Chiastolite, and *Staurolite-schists* are those in which certain aluminous silicates are more completely developed, so that the mineral species are recognizable. Both these and spotted-schist occur chiefly in the metamorphic zones surrounding igneous masses.

Hornblende-schist consists essentially of hornblende, felspar, and quartz, hornblende generally predominating, while in some varieties there is little felspar, and in others very little quartz. The hornblende forms long lenticular bands alternating with thinner layers of quartz or felspar. Most hornblende-schists appear to have been derived from basic igneous rocks.[1] "In the field diorites, dolerites, and aphanites can be seen to pass into hornblende-schist.

Chlorite-schist and *Talc-schist* are schistose rocks in which these particular minerals predominate, but many so-called chlorite-schists are merely green mica-schists. Garnet, epidote, and magnetite are frequently present in these schists.

Serpentine-schist is probably in most cases a cleaved Serpentine.

[1] See Teall on the "Metamorphosis of Basic Igneous Rocks," "Proc. Geol. Assoc.," vol. x. p. 58.

Calc-schist is a schistose limestone in which accessory silicates have been developed during metamorphism; silvery mica is frequent in such altered limestones, and occasionally tremolite, as at Shinness in Sutherland. Serpentinous marble or ophicalcite is often schistose. *Calc-mica-schist* is a variety formed from impure limestones; the chief constituents are quartz, calcite, and mica arranged in foliated layers, the mica being sometimes rendered nearly opaque by black carbonaceous dust. Dolomite sometimes occurs in place of calcite.[1]

Porphyroid and Schalstein are schistose rocks, the one of an acid, the other of a more basic character, whose origin is rather obscure, but probably in many cases they are volcanic tuffs altered by pressure and by chemical changes. In other instances they appear to be compact igneous rocks which have been similarly altered.

Gneisses.—These are foliated rocks consisting of quartz, felspar, and mica. They may be coarse or fine in grain. Recent research tends to the conclusion that most of them are foliated igneous rocks, and some geologists doubt whether any true gneiss has originated from a sedimentary rock. When no shearing from movement under pressure has taken place the rock is granulitic, when sheared it is crumpled, and when crushed may be mylonitic. Eye-structure is often very clearly displayed.

Ordinary gneiss consists of quartz, felspar and biotite, the felspar being usually orthoclase, arranged in short lenticular folia, and some of it in large "eyes": the quartz is often in knots and bands. Garnet is frequently present, while chlorite, epidote, graphite, etc., are common accessories. *Protogine* is a variety with altered magnesian mica, which has been mistaken for talc. *Cordierite-gneiss* is a gneiss containing cordierite or dichroite, a silicate of alumina (with some iron and magnesia), of a clear blue colour. When hornblende occurs, the rock is called *Hornblende-gneiss*.

If these varieties are compared with those of granite and tonalite, it will be seen that they closely correspond, and it may also be observed that when foliation is not strongly

[1] See Bonney on "Crystalline Rocks of the Alps," "Quart. Journ Geol. Soc.," 1889, vol. xlv. p. 103.

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conceivable, and undoubtedly there are cases where it is very hard to distinguish, in the present state of our knowledge, between an igneous and a metamorphic rock; but it is certainly a fact that the majority of instances brought forward in proof of this extreme metamorphism have broken down on careful examination."[1]

[1] From MS. notes by Professor Bonney, who adds, that "since this was written the advance of knowledge has shown that granite has, in many cases, been converted into gneiss, while no case of a granitic rock having been formed out of a mass of schist or gneiss has been established."

CHAPTER XIII.

METAMORPHIC ROCKS.

Considered as Rock-Masses.

IN the preceding chapter the metamorphic rocks have been described from a lithological or petrological point of view. We have now to regard them as rock-masses or components of the earth's crust; first describing the relations which their special structural planes (*i.e.*, cleavage and foliation) bear to stratification and to one another, and discussing the evidence of the manner in which these structures have been produced; secondly, describing some actual cases and areas of metamorphism.

1. Cleavage Planes.

Dip and Strike.—The planes of cleavage may be said to have a dip and a strike just in the same way as planes of stratification. Their angle of dip varies from the vertical to as little as 10°, but is more frequently between 50° and 80°.

Fig. 173 illustrates the varying relations between the inclination of the strata and that of the cleavage planes. A represents a section near Llandovery in Wales, where a series of quartzose grits and sandstones are inclined at an angle of about 40°, and the cleavage planes dip in the same direction, but at a much greater angle. In B the cleavage planes dip in the same direction, while the strata are inclined in the opposite direction. In both cases the strike of the cleavage planes coincides generally with that of the

strata. Occasionally, when the strata have high dips, it happens that the cleavage planes very nearly coincide with those of the bedding and lamination.

Their strike is generally constant over considerable areas, and parallel to the direction of the axes of the principal flexures. This coincidence between the strike of the cleavage planes and that of the strata is of itself strong evidence that the cleavage was caused by the same pressure as that which caused the plication of the rocks.

One of the best examples of this steady direction in the strike of cleavage planes is the south of Ireland, over the whole of which, from Dublin to Mizen Head, the direction of the cleavage seldom varies much from E.N.E. and

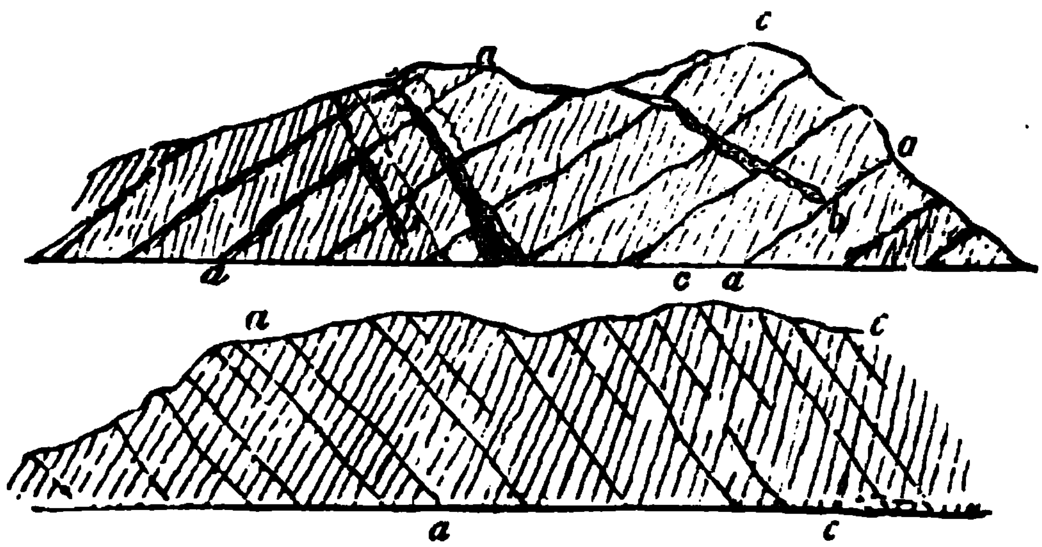

Fig. 173. Relation of Cleavage to Bedding.

a a, Bedding planes. *c c*, Cleavage planes.

W.S.W., whatever rocks it traverses, and however different these rocks may be in lithological character and geological age. The strike of the main axes of flexure is likewise steady in the same direction. The planes of cleavage are inclined at very high angles, which generally approach the perpendicular, but when they have a dip, it is always to the S.S.E., and this southerly dip appears to be connected with the special form of the curves into which the strata have been bent. These are not mere undulations with vertical axes, but are pushed over in a northerly direction, so that their axes are oblique, and the strata are slightly inverted on the northern side, as if the pressure by which they were produced had acted most strongly

from the south; the dip of the cleavage is therefore roughly parallel to the dip of these oblique axes, both being due doubtless to the same cause.

It may, indeed, be stated as a general rule, that when the axes of the folds and flexures are inclined from the perpendicular, the average dip of the cleavage planes will be in the same direction.

North Wales is another good field for the study of cleavage. Fig. 174 is a section through the Snowdon chain, from the Menai Straits in a south-easterly direction; the beds, *c c c*, are conglomerates, the other beds being parallel to them, and the fine striæ are cleavage planes striking with the beds to the N.E., but cutting across them in the direction of the dip; for while the beds undulate at

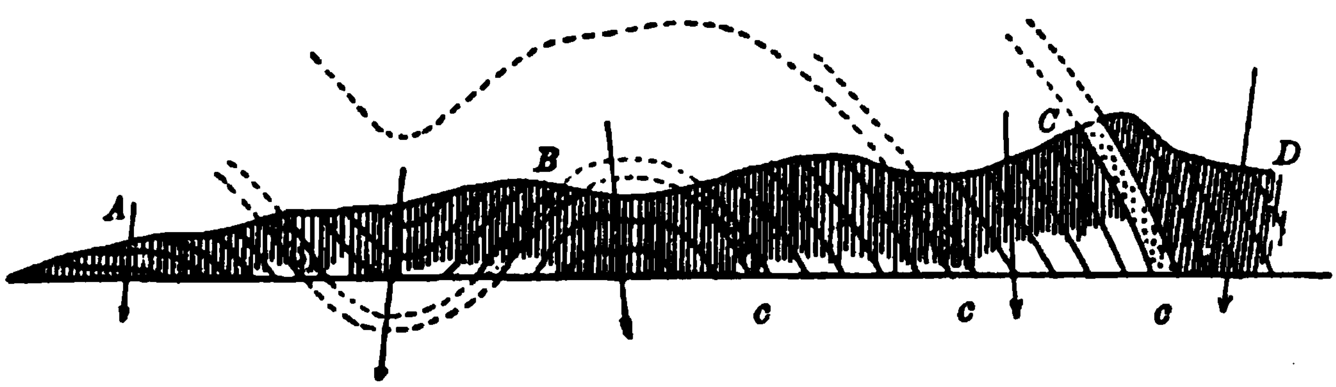

Fig. 174. Cleavage in North Wales (after Jukes).

The fine lines indicate cleavage planes, but should have been drawn parallel to the arrows which show the slight variations in their dip.

various angles, the cleavage dips slightly on either side of the vertical, viz., N.W. at 80° or 85° from A to B; S.E. at 80° to 85° from B to C; and 80° to the N.W. from C to D. From these facts it may be inferred that the rocks were folded first and cleaved afterwards, though possibly not long afterwards; and that some slight movements had taken place after the cleavage was set up.

In North Wales the prevailing strike of the cleavage is N.E. and S.W., because this is also the direction of the main lines of flexure; but where the strata are bent round so as to have a different strike, the strike of the cleavage is altered in a similar manner, so as to coincide with that of the beds.

" In the Berwyn chain, where the beds curve regularly round, from a N.E. and S.W. strike along the Bala and

Corwen valley, to an E. and W. strike along the vale of Llangollen, the strike of the cleavage follows with equal regularity, the cleavage plains dipping W. 20° N. at 30° in the country between Bala and Llangynnog, curving round as they approach Corwen, and striking nearly due E. and W. on both sides of the Dee, between Corwen and Llangollen, with a dip almost invariably to the north at a high angle."[1]

Cases have been noticed where the dip of the cleavage appears to have some connection with the dip of the beds. Thus Darwin has described instances in South America where the cleavage planes dip inward on either side of large anticlinal curves, so as to exhibit a fan-like arrangement; but such exceptions to the general rule are probably explicable on the supposition that the dip of the cleavage has been affected by subsequent movements, the cleavage being antecedent in point of time to the production of these particular sets of anticlinals. It is quite possible that a district may at one period of time be subjected to very great compression, capable of producing both contortion and cleavage; and that after a period of quiescence, during which the beds acquired fixed positions, renewed compression may give rise to another set of curves, or even to a second set of cleavage planes. The range of the Andes is exactly one of the districts where we should expect to find evidences of repeated periods of compression, because there is other evidence that its elevation has been the result of repeated movements (see p. 70). Cases in which a second set of cleavage planes have been noticed, with a different strike or dip to the first set, are mentioned by Sedgwick, Phillips, and others.

Influence of Rock-texture on Cleavage.—Cleavage is always most perfect in the finest grained rocks, splitting them into an indefinite number of thin plates. The coarser the rock, the fainter, the wider apart, and the more rough and irregular do the cleavage planes become; and in the case of thick-bedded sandstones cleavage generally divides the rock into coarse slabs only, the upper and under surfaces of the beds often breaking into dog-toothed

[1] Jukes' "Manual of Geology," second edition, p. 267.

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study and in the field. By microscopical examination Mr. Sorby found that the minute particles of slate lie more flatly in the cleavage planes than in any other direction; whence he inferred that they had been lengthened in the direction of the cleavage planes, or else, if they were originally of unequal dimensions, they have been rearranged so that the longer axes coincide with the planes of cleavage. Mr. W. M. Hutchings says: "The base and main constituent of all these slates (from Wales and Cornwall) is a small grained mica, mostly lying flat in the planes of cleavage of the rock."[1] In the case of coarse-grained rocks this rearrangement of the component particles may be easily observed; thus, Sir A. Ramsay describes a conglomerate near Llyn Padarn in Caernarvonshire as consisting of slaty pebbles in a slaty matrix, the whole being affected by cleavage remarkable on account of the pebbles being rearranged with their longer axes parallel to the cleavage planes, and looking as if they had been elongated or pulled out in that direction.[2]

Professor G. Cole[3] describes the microscopic structure of slate in the following terms:—"All the microlites and grains seem lying with their longer axes parallel with one another. . . . The transparent constituents can sometimes be identified as mica. . . . The black amorphous clay particles or groups of kaolin flakes are pressed out into extremely flattened lenticles, so that when cut perpendicularly to the cleavage surfaces fine dark lines run parallel and close-set through the slide."

The same appearances are exhibited by the fossils which occur in slate rocks; their dimensions are always changed, so that the fossil is distorted, being lengthened in one direction, and shortened in another. Thin shells such as *Lingulæ* and the tests of *Trilobites* are especially affected, the latter being sometimes minutely wrinkled in lines parallel to the cleavage.

It may also be observed that when harder beds, such as bands of sandstone or limestone, occur among slates, they

[1] See his papers on the "Probable Origin of some Slates," "Geol. Mag.," 1890, pp. 264 and 316.

[2] "Geology of North Wales," "Mem. Geol. Survey," p. 145.

[3] "Aids in Practical Geology," Griffin and Co., 1891.

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Conditions necessary to produce Cleavage.—The origin of cleavage has recently been discussed by the Rev. O. Fisher, who thinks that the phenomena indicate something more than mere compression and packing of the rock-particles, and believes that a movement of the nature of a *shear*, causing an actual elongation of these particles, is necessary for the production of cleavage.

A shear is the result of a stress or pressure so applied as to make one portion of a body move over another portion. When the form of a body under stress is permanently altered without solution of continuity, it is said to be plastic, and the movement of a plastic body under shearing stress may be called a *viscous shear*. When the stress is so great as to overcome the friction of the component particles the body shears as a solid, that is to say, it gives way along certain planes and breaks into slices, each of which moves over that beneath it. The planes thus formed are called *shear surfaces*, and the thrust faults described on p. 454 are surfaces of this kind.

In his earlier papers Mr. Fisher assumed that cleavage planes were also shear surfaces,[1] but subsequently perceived that they could not be such surfaces, and now regards them as resulting from the elongation of the component particles by a viscous shear.[2] He describes a case in which the cleavage of a slate is crossed obliquely by what appear to be planes of shear, and he shows that if a circular area were sheared between two of these planes it would be distorted into an ellipse, the longer axis of which would be nearly parallel to the cleavage. Hence he concludes that it was the elongation of the rock-particles by the shear which gave the rock its cleavage. In Mr. Fisher's own words, "it is due to the deformation of the constituents of a (comparatively) homogeneous and ductile rock,

[1] "Geol. Mag.," Dec. 3, vol. i. p. 271.

[2] *Op. cit.*, p. 398, and "Physics of the Earth's Crust," second edition, p. 269.

and it follows the flattened faces of the deformed particles." (*Op. cit.*, p. 370.)

Mr. Fisher has been kind enough to explain by letter more fully what he means by "deformed particles," and it seems he means small aggregations of particles, or what may be termed molecules; but as the existence of such molecules in slates is very doubtful, and as it is certain that the individual mica-flakes lie in the planes of cleavage, the author cannot accept Mr. Fisher's view, but believes that cleavage is a result of the rearrangement of the component particles of a rock. At the same time, he admits that a mass of clay or shale compelled to change its dimensions will shear, and that the resulting movement may be such as will satisfactorily explain the distortion of fossils, pebbles, or nodules contained in the mass.

It must be remembered, however, that a shearing stress may cause more than one kind of movement within the mass, and that the particular movement considered by Mr. Fisher may be only the final movement developed by the continued pressure. The pressure, or the stresses set up by it, act more or less horizontally, and cause compression combined with upward expansion; and it is quite conceivable that the first result of such compression of a plastic mass consisting chiefly of minute flattish particles would be to cause a kind of irregular upward flow, during which the particles, by mutual friction among themselves, without elongation or deformation, would be simply rearranged with their broad sides facing the pressure and their longer axes in the direction of least resistance. This seems to be the view held by Sorby, Tyndall, and others, who actually produced cleavage in various substances by subjecting them to compression, only they did not call the motion of the component particles a shear.

But a cleavage so produced will not entirely account for the distortion of fossils above mentioned: here Mr. Fisher steps in, and shows that if the final result of the shear is to cause the component particles to move along parallel planes, any spheroidal area in the compressed mass will necessarily be deformed into an ellipsoid; this will apparently take place by a slipping of the particles past one another without disturbance of their parallel positions,

but perhaps with a tendency to bend or incline them in the direction of the shear; that is to say, the shear forces them to take up a position which is represented by the direction of the longer axis of the ellipsoid of distortion. Such a movement is just what is likely to happen when a force is overcoming the resistance offered by the cohesion of the particles, and when carried a degree further it will result in the development of shear surfaces such as appear in the case referred to by Mr. Fisher.

There are also some cases where the cleavage planes do coincide with shear surfaces; the Ausweichungs-clivage of the Germans, for which Prof. Bonney has proposed the name "strain-slip cleavage."

If the view just expressed is correct, there must be cases of cleaved rocks without distortion of fossils, such bodies only showing elongation parallel to the planes of cleavage. It is believed that such cases do exist, but this point requires further investigation.

It has been observed (1) that in many cases the pressure has come from one definite direction, and (2) that where large masses of very hard rock occur in a cleaved area the cleavage is always most strongly developed on the side which faced the pressure, and (3) that in such localities shear surfaces are often observable, but that they have a steep inclination and cut obliquely across the cleavage; these are facts which seem to indicate the following as being the conditions necessary for the production of cleavage:—

A resistant mass, or several such masses, of hard rock, which serve as relatively fixed abutments, a lateral force producing compression of the softer and more plastic rocks against these abutments, and causing an upward extension of the plastic beds, accompanied by such a rearrangement of their component particles that the flat flakes of mica and kaolin come to lie in parallel planes.

Continued application of pressure to such a mass may develop a shearing stress, the motion taking the direction of least resistance, which under such conditions will be obliquely upward, pulling out the rock-mass in that direction, and ultimately overcoming the friction and producing shear surfaces. The difference between this shear and that

producing a horizontal thrust plane or shear fault, is that in the one case the force was not sufficient to overcome the resistance of the abutment, in the other it was. Hence the difference in the hade of the shear planes, the one hading at a high angle, the other at a low angle. This difference may be seen also in the section, fig. 178, where the reverse faults with steep hades have probably been formed before the resistance of the abutment was overcome, while the thrust planes were formed after this abutment gave way. In the N.W. of Scotland the abutment was evidently the gneissic mass of the Hebrides.

We may conclude, therefore, that a region undergoing compression will first have its component strata flexed and folded; continued or subsequently renewed pressure will cause, first cleavage, then reversed faulting, and finally more or less horizontal over-thrusts.

Foliation.

Until recently, writers on foliation were much occupied with the question whether foliation coincided with cleavage or with stratification. Sedgwick and Darwin were of opinion that foliation was almost always coincident with cleavage, and that it was, in fact, only a further development of the same process. Sedgwick, however, then believed that cleavage itself was produced by the action of crystalline and polar forces, instead of by pressure.

Jukes maintained that the coincidence of foliation with cleavage was only an accidental one, and that it was only likely to occur in cases where a considerable thickness of argillaceous deposits had been converted into a tolerably homogeneous mass of slate before it was subjected to the further metamorphic processes which produced foliation.

Lastly, it was the unanimous testimony of observers in the metamorphic areas of Ireland and Scotland that in those countries the foliation appeared to coincide with the original stratification, and they appealed to cases where quartzites and limestones were interstratified with schists, the foliation of the latter coinciding with the dip and strike of the former.

It was therefore the general conclusion that foliation coincided either with cleavage or with stratification, and more often with the latter; and it was inferred that the arrangement of the crystalline minerals in folia was regulated by the previously-existing lines of separation.

The fact is, the structure called foliation has not always been produced in the same way, and there are probably at least three different processes by which this structure may be set up.

Recent researches, especially those of Lapworth and Callaway, and more lately by the officers of the Geological Survey, have demonstrated that in regions like the north of Scotland the main planes of schistosity or foliation are those of shear under intense lateral pressure, and that the foliation is developed with the same direction through stratified and unstratified rocks alike. In the words of Professor Lapworth,[1] "the planes of schistosity are those along which the rocks yielded to the lateral pressure. . . . These planes cut the rock up into lenticular patches or phacoids, which, like the yielding planes themselves, are of all gradations of size, from the mountain masses riding out along the great overfolds and overfaults down to the "eyes" of *augen-schists*. The mechanical effects wrought by the shearing and deformation of the phacoids show of necessity a corresponding gradation, the conditions at one extreme giving rise to coarse rock-breccias; in medium cases to *flaser* structures and foliation; at the other extreme to compact stringy *mylonite*, in which the original material has been torn and ground to rock-dust. Parallel with these *mechanical changes*, but not necessarily accompanying them, we note a series of *chemical changes* of rising grades of importance, a larger and larger portion of the rock which is undergoing deformation becoming recrystallized, until finally it may all be transformed into foliated crystalline rock."

The varieties of the schists produced in this way are due partly to the relative degrees of alteration, and partly to the original differences in the structure and composition of the rocks acted upon; for what are now schists may

[1] In Page's "Introd. Text-book of Geology," twelfth edition, p. 113.

have been originally either sedimentary or igneous rocks, or even gneisses and schists formed by a previous metamorphism. "In fine," to quote Professor Lapworth again, "a metamorphic area is a petrological complex whose altered rocks have a common foliation. The *strike of foliation* in such a district is related to the general strike of the sheets of sedimentary or crystalline rocks which formed its main masses at the time of its final folding and shearing: the *dip of the foliation* is simply the local direction of shear, *i.e.*, is related to the direction in which the mass was giving way."[1]

Professor Bonney, however, maintains that this is not the only way in which foliation is produced. He fully admits that pressure has been the chief agent in producing the more prominent schistose structures of the north-west Highlands, but thinks that foliation often exists where there is no cleavage and no shearing, and where the mineral banding has clearly been guided by the stratification of the materials. He mentions districts where both kinds of foliation are distinguishable in the same mass of rock, the stratification-foliation being always the first-formed and generally dominant, though sometimes more or less obliterated by subsequent pressure-foliation and shearing structures. In the Swiss Alps this secondary foliation, due directly to pressure, "may be traced in every degree, from the stage where the sheen surfaces are quite subordinate to the stratification-foliation, to that in which the latter has been wholly obliterated by cleavage-foliation, when the rock splits up into thin slabs, sometimes almost films of a friable micaceous schist which we might almost call a slate."[2]

There is, moreover, another way in which foliation may be produced, to which attention has recently been directed by General Macmahon and Professor Bonney, in connection with the foliated gabbro of the Lizard district. This rock

[1] I have given Professor Lapworth's description of pressure metamorphism, not only because it is tersely and clearly expressed, but because he was the first to publish the deformation theory in its complete form, and to explain the structure of the Scottish Highlands.

[2] "Pres. Address tc Geol. Soc.," 1886, p. 69.

there occurs in dykes which break through serpentine and schist, and some parts of these dykes are distinctly foliated; the foliation is generally parallel to the walls of the dykes, often occurring only near the walls, but sometimes trending inwards obliquely and blending into the unfoliated portion of the mass. The folia are in some cases so thin and small that the rock resembles a schist, but in other parts the grain is coarse and "eye" structure is not uncommon.[1] The authors above mentioned regard this foliation as a kind of fluxion structure produced by movements in the mass when it consisted of crystals floating in a viscid magma, and when its outside portions were on the point of solidification.

Banded Gneiss.—There is still another structure exhibited by certain rock-masses which is somewhat analogous to fluxion-foliation, but is on a larger scale. In these rocks distinct layers or bands of different rock-material alternate with one another in such a manner as to simulate stratification. Thus the banded gneiss of Cornwall consists of a dark dioritic rock veined or banded with a light-coloured rock which resembles a fine-grained granite or eurite. There is no evidence of intense pressure or crushing, and it is supposed that this banding has been brought about by the injection of an acid magma into a basic magma or rock, the former having a high temperature and so far softening the latter that it was pulled out and made to flow with the more liquid material; the two kinds of rock-stuff being thus welded together without being completely mixed before the final crystallization took place.[2]

The folia of schists are frequently wrinkled and corrugated in a remarkable manner, giving the rock a peculiar crumpled and gnarled appearance. Sir A. Ramsay has suggested that these very lines are those of a previously induced cleavage which was only partially obliterated by the foliation, the planes of cleavage being bent and crumpled by farther

[1] "Quart. Journ. Geol. Soc.," vol. xlvii. p. 487.

[2] Bonney and Macmahon, "Quart. Journ. Geol. Soc.," vol. xlvii. p. 477. See also a paper by Messrs. Hill and Bonney on the Schists and Gneisses of Sark, read before Geol. Soc., Jan. 20th, 1892, in which they describe the genesis of a banded biotite-gneiss out of a hornblende rock invaded by a fine-grained granite.

pressure when the mass was in a plastic condition. This explanation assumes the existence of a previous cleavage, and it is possible that in many cases the corrugation is simply due to subsequent compression acting on the folia of a schist, and that it is therefore analogous to the crumpling of the original laminæ of a slate. It may be the effect of pressure acting on the mass after the layers or folia had been formed.[1]

2. *Areas of Metamorphism.*

The reader may already have gathered from statements in the preceding pages that the metamorphism of rocks has not been accomplished by one set of agencies only, or under one set of physical conditions. As a matter of fact, the rocks which are usually grouped together as *metamorphic* have resulted from the operation of several distinct physical processes; one being the intrusion of large masses of igneous rock, another being the development of stresses and strains in a portion of the earth's crust. While as to the manner in which stratification-foliation has been produced over large areas we must at present be content to confess our ignorance. It is possible that in time the microscope will disclose the existence of radical differences between rocks formed in such different ways, and it is already certain that some varieties of rock are only formed under certain conditions. It is therefore desirable to distinguish clearly between the different kinds of metamorphism: the first has been called *Local or Contact Metamorphism,* the second *Pressure Metamorphism,* the third *Regional Metamorphism.*

Local or Contact Metamorphism.—Some of the metamorphic effects produced by the intrusion of igneous rocks have already been mentioned. The mutual alteration resulting from the contact of granite veins with limestone was mentioned on p. 485; again, the manner in which a mass of slate may be altered into mica-schist by the

[1] This passage remains as printed in the first edition; the view expressed has been confirmed by recent observations in Scotland. See "Quart. Journ. Geol. Soc.," 1888, p. 378.

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and losing its fissile character, though the lines of lamination are still visible; near the dolerite it is converted into a hard jaspery porcellanite, while crystals of garnet and analcime are developed more or less throughout the altered portion of the shale. The limestone undergoes similar alteration, becoming gradually compact and crystalline in approaching the trap.

It often happens, too, that the igneous rock itself is likewise altered near the contact surfaces, especially if it is intruded into rocks of a calcareous or carbonaceous nature; basalt often loses its dark colour, assumes tints of pink and green, or even becomes quite white, and chemical analysis shows that such white traps contain from 9 to 10 per cent. of carbonic acid, and 10 or 11 per cent. of water.

Excellent instances of such mutual metamorphism occur in Fifeshire, which has been the scene of extensive and repeated volcanic intrusions. The results of one of these intrusions may be studied on the shore at Ross End near Burntisland, where the calciferous sandstones are invaded by a sheet of dolerite. The sandstones are converted into quartzite, and all stages of alteration can be traced in the lower part of the dolerite, passing from dark green, through light green, to pink and white, and in one place it is bright red, with amygdaloidal inclusions. The main sheet sends off intrusive branches and veins of white trap into the quartzite, fragments of which have been broken off and included in the igneous rock.

Similar instances are found in the South Staffordshire coal-field, as described by Mr. Jukes,[1] who specially mentions one in the Grace Mary colliery, where a part of the Tenyard coal and associated sandstone is penetrated by an irregular sheet of white earthy trap, which has probably proceeded from the black basalt of the neighbouring Rowley Hills. The sandstone has not been much altered by the contact, but the coal has lost its bright lustre and much of its inflammable character.

Alteration by Granitic Masses.—1. As an instance where the effects of intrusive bosses of igneous rock can be easily examined we may take those of Cornwall. In this county

[1] "Geology of S. Staffordshire Coal-field, Mem. Geol. Survey."

four bosses of granite, which are probably parts of one continuous underlying mass, are intruded into the clay slates which are locally termed *killas*. The metamorphic zone surrounding any of these bosses varies from a quarter to half a mile in width; within these limits the killas is converted into micaceous schist, and in the immediate neighbourhood of the granite into a still harder semi-crystalline and compact felspathic rock (*hornfels*).

2. The metamorphism of the Silurian slates by the granite of Leinster, already described (pp. 481 and 482), supplies an instance in which a still wider zone of rock has been altered in a similar way. Mr. Jukes has given the following description of this district:[1]—"The great mass of granite which has been intruded into the clay slates of Leinster forms a continuous range of granite hills from Dublin Bay to the neighbourhood of New Ross, a distance of 70 miles. Between this range and the coast other smaller intrusive bosses make their appearance at the surface. The unaltered clay slates exhibit various tints of dull grey, green, blue, purple, and black; they are always without lustre, and generally of a dull earthy texture. Small bands of grey siliceous grit often occur in them.

"Wherever the granite comes to the surface a belt of slates surrounding it is converted into mica-schist, with, in some few places, beds that might be called gneiss. Crystals of garnet, schorl, andalusite, staurolite, etc., make their appearance in these altered slates in greater and greater abundance as they approach the granite. The width of the metamorphosed belt is generally proportioned to the size of the granite mass which it surrounds. Round the smaller granite bosses it is sometimes not more than 50 yards wide; round the main granite mass it sometimes reaches to two miles. It matters not through what part of the slate rocks the granite rises, or which beds strike towards the granite,—they are all found to be affected in the same way as they approach it.

"In going towards the main granite ridge it is found sometimes at a distance of two miles from the outcrop of

[1] "Students' Manual of Geology," second edition, p. 275.

the granite (which, is, however, much nearer probably in a vertical direction), that the slates have acquired a 'glaze,' as it were, or micaceous lustre, with a soapy feel. This micaceous appearance increases as we approach the granite, till at last distinct plates and folia of mica are to be seen, and the whole assumes the ordinary character of mica-schist, occasionally passing into a kind of gneiss. Some of these gneissic layers are obviously beds of sandstone originally interstratified with the shales, the rocks having all the appearance of interstratified shale and sandstone at a distance, and until they are broken open, and are found to have the aspect of mica-schist and gneiss."[1]

By French writers the term *aureole* has been introduced to designate the concentric zone of metamorphosed rocks which surrounds an intrusive mass of igneous rock. Thus, in describing the phenomena of contact metamorphism round the granitic bosses of Asturia in Spain, Dr. Barrois says: "The first metamorphic effect is simply a change of structure, consisting of the development of a crumpled or goffered structure, without any new combinations being formed among the elements of the rock. Nearer the granite the metamorphic effect is different and more intense; the minerals whose substance is disseminated in a pulverized state within the rock have crystallized in consequence of molecular changes, the particles of a similar nature being attracted to one another," and forming crystals of mica, chiastolite, etc.[2] These chiastolite shales become more and more micaceous as one approaches the granite, until they become regular foliated schist. Three distinct concentric zones can, therefore, be recognized in the *aureoles* round the granites of Asturia, and may be distinguished as follows, commencing with the outermost:—

1. Zone des schistes gaufrés (wavy schists).
2. Zone des schistes maclifères (spotted schists).
3. Zone des Leptynolithes (gneissic and quartzose schists).

[1] The reader will see that Jukes is only describing the general aspect of the rocks, which do not really exhibit the microscopical structure of mica-schist and gneiss.

[2] "Recherches sur les terrains anciens des Asturies et de la Galicie, Mem. Soc. Geol. du Nord," tome ii. 1882, p. 92.

Dr. Barrois is careful, however, to point out that this succession of aureoles is only true in a general sense, and that layers of micaceous schist with crystals of chiastolite are often intercalated among the less highly metamorphosed schists. Such intercalations are doubtless dependent upon differences in original mineral composition, the crystals being more easily developed in some beds than in others.

Describing the effects of the granitic intrusions of the Vosges, Professor Rosenbusch also distinguishes three zones which he terms:—

1. Zones of spotted clay-slate (knoten thon-schiefer).
2. Zones of spotted mica-slate (knoten glimmer-schiefer).
3. Zones of massive hornstone (hornfels).

The hornstone of the innermost zone is a hard, compact rock, sometimes of a jaspery aspect, sometimes more crystalline, and generally containing crystals of andalusite. The microscope showed it to be really crystalline and to consist of quartz, two kinds of mica, andalusite, magnetite and hæmatite.

The effect of granite on a mass of sandstone has been well described by Dr. Barrois in connection with the granite of Guéméné, in Brittany. The unaltered sandstone consists of quartz and white mica with some ferruginous matter. In the first zone the minerals are the same, but both are recrystallized, and the rock is a quartzite; the mica changed to a black variety, probably by absorption of iron. Nearer the granite sillimanite (a variety of andalusite) in acicular crystals and magnetite appear. Close to the granite the rock is traversed by granitic veins of all sizes, and is so impregnated with granitic material that it becomes a felspathic quartzite.

District and Regional Metamorphism.—The cases of alteration above described demonstrate that the intrusion of igneous rock into stratified rock is sufficient to convert portions of the latter into metamorphic rocks by a recrystallization of the rock material. Moreover, since the extent of this metamorphism appears to be roughly proportionate to the mass of the intrusive rock, it might be supposed that the cases of metamorphism on a larger scale were principally due to the proximity of still larger masses

of intrusive igneous rocks. This, however, would be a false inference, for we could not examine many metamorphic districts without finding that the extent of metamorphism was out of all proportion to the mass of purely intrusive rock in the same area. The Scottish Highlands, for instance, consist mainly of metamorphic rocks, yet they do not exhibit any mass of intrusive granite so large as that of Leinster, the alterative effect of which only extends to a maximum distance of two miles. Again, in the Swiss Alps, where the whole mountain masses consist of highly metamorphosed strata, intrusions of granite or other plutonic rock are of rare occurrence, and where they do exist cannot be connected with metamorphic action of any importance.

It is clear, therefore, that the mere contact with deep-seated igneous rock is not sufficient to produce wide areas of metamorphism; but the same study of metamorphic districts which would lead us to discard this hypothesis would elicit the fact that in some districts metamorphic action has always been accompanied by great contortion and plication of the strata with overfolds and overthrusts, and that the amount of this plication and dislocation does appear to have a direct relation with the intensity of the metamorphism.

In such districts everything points to the combined influence of intense pressure and heat, with a resulting movement of elevation. Mr. Mallet has also suggested that the energy of the force employed in crushing and contorting the rocks may be transformed into heat, and that the amount of heat evolved during this process might be sufficient to soften and partially fuse the rocks which are thus affected. But geologists have not found any evidence in nature which tends to support this hypothesis.

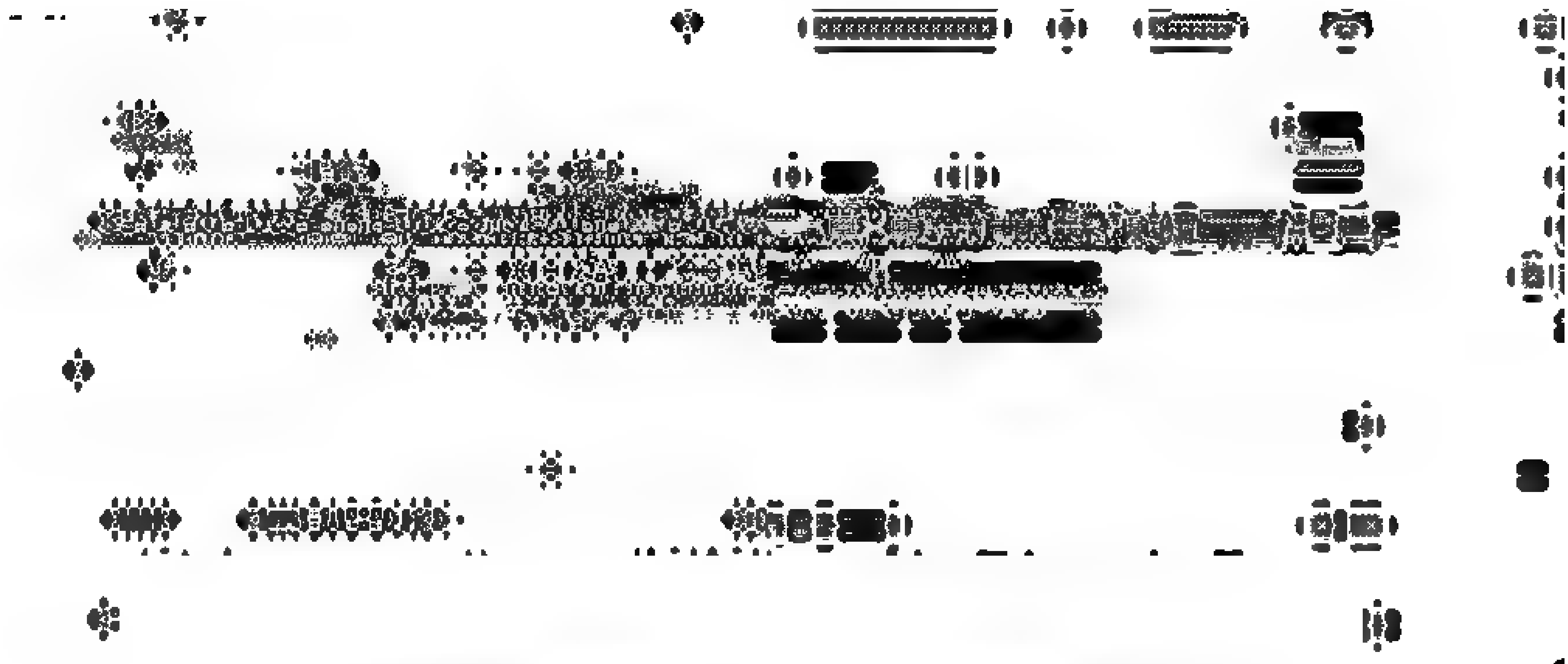
Moreover, Professor Bonney has pointed out that in some metamorphic areas there is very little evidence of pressure, and that in others, *e.g.*, the Alps, there is clear evidence that the pressure did not act till after the rocks had become crystalline. Again, in Scotland there are large areas where the metamorphism is not due to lateral pressure or crushing, though there are certain districts where special kinds of schistose rock have been produced by pressure

out of previously foliated rocks. Professor Bonney consequently maintains that it is a mistake to include these special cases under the head of *regional metamorphism;* this term should be reserved for the larger areas of metamorphic and crystalline rocks, such as the Scottish Highlands as a whole, the crystalline region of the Alps, and large parts of Norway, Greenland, and Canada. The phenomena of the smaller districts, often included in these tracts, which have been modified by pressure may be described under the head of *district metamorphism.*

As an instance of such a district we may take the N.W. Highlands, the phenomena of which have been specially studied by Professors Lapworth and Bonney, Dr. Callaway, Messrs. Peach, Horne, and other officers of the Geological Survey. Three great formations enter into the structure of this region; the lowest and oldest is the basal gneiss of Sutherland and Ross; the second is a massive formation of red sandstone and conglomerate; the third is a series of grits, quartzites, shales and limestones. Before the production of the dislocations and deformations to which the present arrangement of the rock-masses is due, the basal gneiss formed a continuous platform supporting the two other formations; the red sandstones, which are in places more than 4,000 feet thick, thinned out eastward and allowed the uppermost stratified series to rest directly on the gneiss ; the general strike of this series being from N.N.E. to S.S.W., and their general dip being to the E.S.E.

In the western part of the region the original relations of the three formations are clearly visible, and the rocks can be recognized as those above mentioned; it is seen also that the basal gneiss received its foliation before the accumulation of the sandstones. In the central and eastern districts, however, the whole mass has been plicated and dislocated, cut up by reversed faults, and sliced by thrust planes, and the severed blocks and slices have been piled on to one another in a manner that can only be realized by actual inspection of the country, or of the detailed sections drawn by the geological surveyors.[1] At the same

[1] See Report of recent work in the North-west Highlands of Scotland, "Quart. Journ. Geol. Soc.," vol. xliv. p. 378.



f, [illegible]
e, Limestone Series. *b*, Torridon Sandstone.
a, Archæan Gneiss.

It will be noticed that the faults in the western half of the section are of the normal kind, hading to the downthrow, while those in the eastern half are all reversed overthrust faults or thrust-planes.

time, in consequence of these mechanical movements and of the chemical action thereby set up, the rocks have all been converted into varieties of gneiss and schist, and the foliation of the previously existing gneiss has been more or less obliterated by the secondary foliation which it has acquired in common with the other rocks. The igneous rocks too, which occur as intrusive masses and dykes in the stratified series, are in the central district converted into augen-schists, hornblende, and sericite-schists. Fig. 178 is an attempt to give a general idea of the structure of this region, but on such a small scale it is impossible to convey more than a feeble outline. Fig. 179 is a portion of it on a larger scale; and the reader should also refer to fig. 144, p. 454, to realize the kind of faulting.

The following extracts from the Report of the Geological Surveyors describe the extent to which the metamorphism of some of the rocks has been carried.

First, as to the gneiss, they note a gradual increase in the alteration of this rock, and in the obliteration of the first foliation as it is followed from west to east. Describing the belt of sheared gneiss and green schist which underlies the Moine thrust plane, they say: "The Archæan gneiss has been rolled out into a finely laminated slate, or slaty schist (mylonite), breaking into thin folia like leaves of paper. All the various stages of deformation, from the crushed Archæan gneiss on the one hand, to the laminated slate on the other, can be clearly traced. The original constituents of the gneiss have been comminuted, but here and there broken fragments of the felspars occur, which are invariably drawn out in the direction of movement. . . . These finely laminated schists or slates show beautiful examples of fluxion structure, and their foliation-surfaces display closely set lines or 'striping,' indicating the direction of movement of the particles over each other, the general trend of the latter being E.S.E. Associated with these slates are certain belts of 'frilled' dark green schists, a detailed study of which points to the conclusion that they have been formed mainly out of dark hornblendic gneiss, the folia having been piled on each other by minute major and minor thrusts." (*Op. cit.*, p. 430.)

The alteration of the conglomerate at the base of the

red sandstone forms another object lesson in metamorphism. "In its unaltered form this characteristic band of conglomerate is composed of more or less well-rounded pebbles of quartz-rock, gneiss, pegmatite, diorite, &c., embedded in a loose gritty matrix. But where it has been subjected to mechanical movement, the softer pebbles of gneiss and fragments of the basic dykes have been crushed, flattened, and elongated in the direction of movement. Indeed, in some cases they have been drawn out to such an extent as to form thin lenticular bands of micaceous or hornblende-schist flowing round the harder pebbles of quartz-rock. The latter still preserve their rounded form, but they are traversed by small 'step-faults,' tending to elongate them in the direction of movement. The original gritty matrix has been converted into a fine micaceous, or green chloritic schist, showing exquisite flow-structure winding round the elongated pebbles in wavy lines. In short, the matrix has been converted into a fine crystalline schist, and but for the presence of the deformed schistose pebbles it would probably be impossible to tell that the schist had a clastic origin." (*Op. cit.*, p. 431).

In the upper stratified series the grits and quartzites are altered into quartz-schists, the shales are converted into dark micaceous schists, and the limestones into marbles. The dykes of felsite in these rocks are changed into a sort of soft greenish mica-schist, and the diorites into hornblendic augen-schist and gneiss.

In the more eastern districts there are great alternations of flaggy micaceous schist and of coarse micaceous and hornblendic gneiss, traversed in places by bands of pink and grey granite which have been converted into granitoid gneiss by mechanical movements.

CHAPTER XIV.

UNCONFORMITY AND OVERLAP.

THAT dry land has always existed somewhere throughout all geological time we know from the very existence of mechanically-formed rocks, which are the memorials of its erosion and destruction. This axiom was well expressed by Jukes in the following passage: "Lyell long ago showed that the amount of such [detrition and] denudation is to be exactly measured by the quantity of the mechanically-formed aqueous rocks, and as our present lands show us vast sheets of sandstones and clays hundreds and thousands of feet in thickness and hundreds and thousands of square miles in extent, and as every particle of these enormous masses of rock is the result of the erosion of previously existing rocks, it follows that the amount of denudation must have been just as great as that of deposition. Just as when we see a large building we know that a hole or quarry must have been made somewhere in the earth, equal, at least, to the cubical contents of the solid parts of that building; so, where we see a vast mass of mechanically-formed aqueous rocks, we must feel assured that a gap was made somewhere in the surface of the earth equal to the solid contents of those rocks."[1] Conversely, also, when we have ascertained that a large amount of rock material has been removed from any existing, or any ancient land surface, we can be sure that an extensive series of stratified deposits must have been formed somewhere out of the materials thus removed, and that their

[1] Jukes' "Manual of Geology," first edition, p. 280.

deposition went on *pari passu* with the detrition of the land surface.

The oscillations of level which have continually taken place have caused frequent changes in the form of the ancient continents, depressing some parts beneath the sea and elevating other parts, so as to raise portions of the adjoining sea-bottom into dry land. The tracts that formed dry land were constantly exposed to the detritive action of those agencies which were described in Part I., Chapters VI. and VII., and the tracts that sank below the sea were subjected to the planing and levelling action of the sea-waves (Chapter VIII.).

The result of both processes being to remove a great thickness of rock, and the special result of the latter process being to produce the more or less level surface which is termed a plain of marine denudation, it follows that when such surfaces are depressed far below the sea-level, and newer deposits are laid down upon them, there must be a break or discontinuity between the older rocks and the newer deposits. The older series may form a regular and continuous sequence of beds, but the process of deposition having been interrupted by a period of erosion and disturbance, there must naturally be a certain amount of discordance between the older and newer series. Such discordance constitutes unconformity.

The importance of these conclusions cannot be over-estimated, and without a knowledge of the facts and inferences to be described in the present chapter, the student could make but little progress in the study of stratigraphical geology.

Every country has its own geological sequence, comprising a great series of strata, which is divisible into many natural groups or stages, and between any two of these groups there are only two possible relations: they must be either in *conformable* or *unconformable* succession. These terms we proceed to define.

1. Conformable Succession.—Two sets of beds are said to be *conformable* when the base of the upper set rests evenly upon the surface of the lower set, that surface being everywhere one of original deposition. The plane of separation between two such groups simply marks an interval

of comparatively short duration, during which no deposition took place. Two or more conformable groups of beds will therefore form a regular sequence like that of the groups 1, 2, 3, 4, etc., in figs. 108 and 134.

2. **Unconformable Succession.**—Two sets of beds are said to be unconformable when the base of the upper set passes over and across the eroded edges of the lower set, the upper surface of the latter being in fact a surface of erosion. Such a plane of separation involves the lapse of an interval more or less long, during which parts of the beds previously formed were broken up and carried away, leaving a discontinuous sequence or a discontinuity in the stratigraphical succession, as in the lower part of fig. 172,

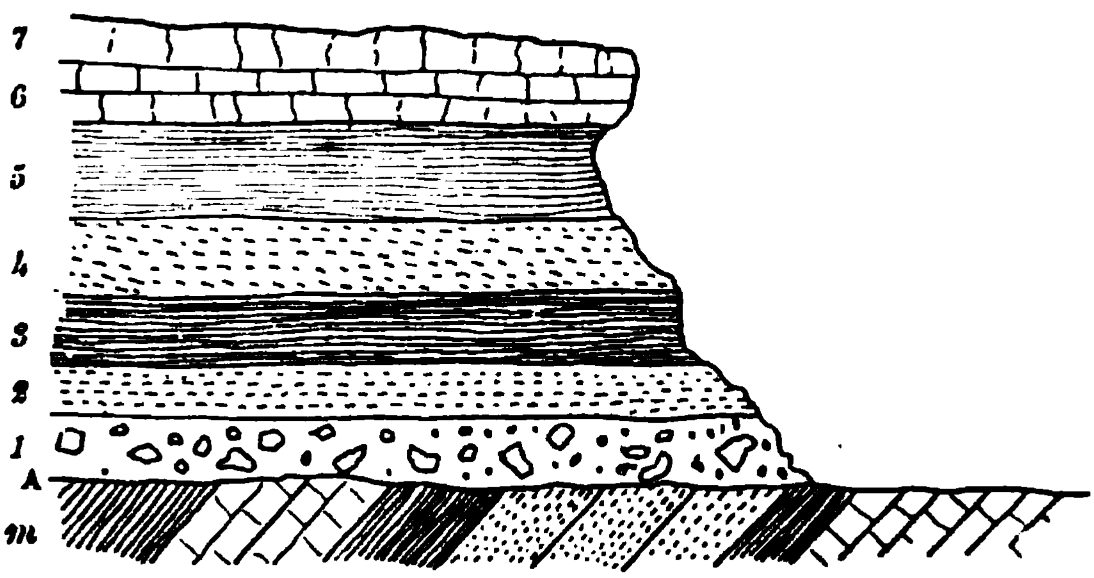


Fig. 180. Unconformity.

where the lower group of beds, *m, m,* have been tilted and planed off till the horizontal surface, A, B, was produced, on which the overlying strata 1 to 7 have been deposited.

This definition of unconformable succession is a very general one, and will include cases which are not generally called *unconformities,* though they are *discontinuities.* There are, therefore, two kinds of discontinuity or irregularity, either of which may cause a break in the regular upward succession of a series of stratified rocks; and, as the distinction between them involves important considerations, it is necessary that they should both be clearly defined.

A. *Contemporaneous Erosion.*—This is a partial discordance caused by the erosion of channels and hollows in a lower group of beds before the deposition of the overlying

group. Thus in fig. 181, a channel has been eroded out of the beds c, c, and the succeeding strata, s, s, have been deposited horizontally upon the uneven surface thus produced. In such cases the erosion has only been local and partial, and other exposures of the two groups would show that in most places the beds s, s, rested evenly and conformably upon the beds c, c. It is obvious, moreover, that if the deposits were subsequently tilted, they would both be inclined at the same angle, and would strike in the same direction.

B. *True Unconformity* involves complete and widespread discordance, and may be defined as the superposition of one group of beds upon the upturned and eroded edges of another group (as in fig. 180). In other words, the dip and strike of the two groups, when both are tilted, will be different. In such cases the interval between the two

Fig. 181. Contemporaneous Erosion.

groups must have been long enough for great geographical changes to have taken place; these must have included the elevation of the lower group, the production of a land surface, and the subsequent depression of this surface below the sea. Sometimes the difference of dip is so slight that it only becomes apparent after a large area of ground has been surveyed. In other cases the faulting of the older beds before the deposition of the newer, as in fig. 142, or their flexure and contortion as in fig. 187, renders the fact of unconformity easy to detect.

The occurrence, then, of a strong unconformity with a marked discordance of dip may in itself be taken as proof that dry land existed for some time there during the interval between the formation of the two series of strata. But a case of contemporaneous erosion only proves that the lower beds have been brought within the action of currents, without being raised above the surface of the sea in which they were desposited.

The student must understand that, in many cases, the existence of an unconformity between two formations can only be ascertained by observing several points of junction, or by mapping the country. In some cases a single exposure, such as a cliff section, may leave no reasonable doubt as to the relations of two formations; but in other cases it would be impossible to say, from the inspection of one exposure, whether a discordance therein visible was local or widespread. The difference of dip may not always be discernible in a single small exposure, and the strike of the upper formation may even coincide for a short distance with that of the lower series. If, however, the boundary

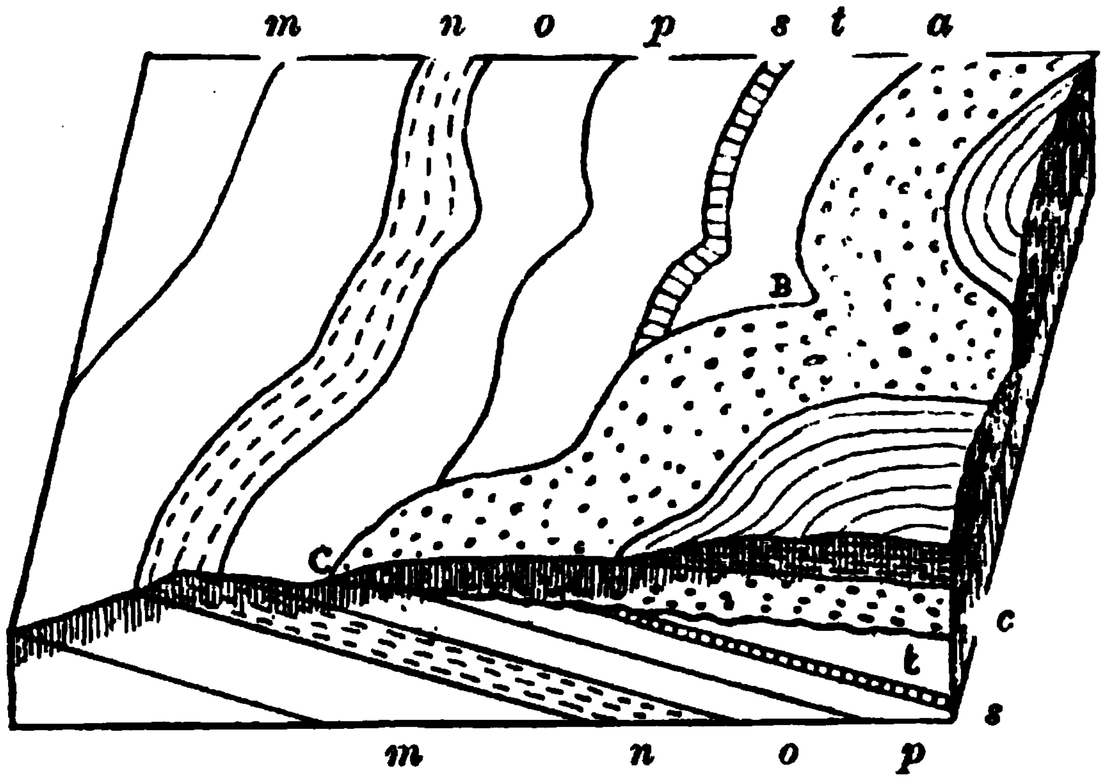


Fig. 182. Diagram to illustrate Unconformity.

line of the upper series is followed across the country, the observer will soon ascertain whether it passes across the outcrops of some of the members of the lower series, as it must do if it has a different strike and dip.

Fig. 182 is intended to represent a geological model of an area where two formations, separated by an unconformity, are dipping in the same direction, but with a different inclination.

It will be seen that though for a short distance between A and B the boundary of the upper formation is nearly parallel to the strike of the lower beds *s*, *t*, *p*, yet between

B and C it passes obliquely across them, and is really unconformable to them, as shown by the profile section, where the bed C C rests on the upturned and eroded edges of the beds *o, p, s, t*. C C may be taken to represent a coarse sandstone, and A B C will indicate its line of outcrop.

The basement beds of a formation which rests unconformably upon another are frequently conglomerates or pebbly sandstones; they represent the beach deposits which were formed along the shore lines of the old land, and were spread out over its surface as it sank beneath the sea, in which the newer overlying strata were accumulated. It must not, however, be supposed that an unconformity is everywhere accompanied by pebble beds; they will generally be found somewhere along the boundary line of an unconformable series, but may be local and

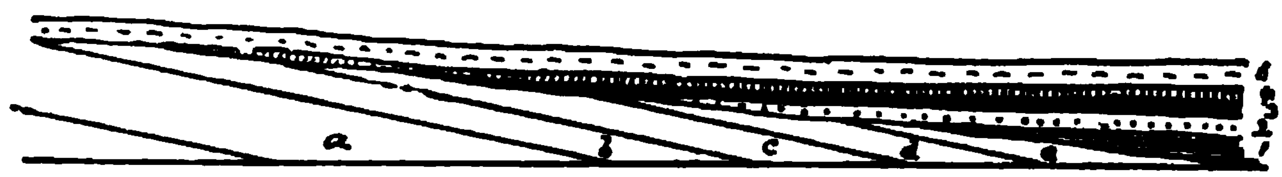


Fig. 183. Overlap and Overstep.
a b c d e, Jurassic Rocks. 1 2 3 4 5, Cretaceous Rocks.

lenticular beds, just as the shingle beds on our own shores are local and discontinuous deposits; so that some parts of the old land surface may not have any such coarse deposits upon them.

Overlap may be described in this place, because the occurrence of overlap is dependant on the existence of an unconformity. The term itself, however, does not denote any relation of a newer series to an older, but applies merely to the relative extension of beds in a conformable series. Overlap occurs in a conformable series when each succeeding bed stretches beyond the limits of that below it in one or more directions, so as to have a wider extension, and to conceal the edges of the lower beds.

In fig. 183, it will be seen that the upper series of beds, 1 2 3 4 5, have a continually increasing extension, 2 extending further west than 1, 3 further than 2, and so on. It is also clearly seen that the overlapping beds are conformable to one another, though unconformable as a

series to the rocks below. Overlap is indeed a necessary consequence of the underlying surface of denudation being an inclined plane instead of a horizontal one, consequently any slope in an area of subsidence will give rise to the phenomena of overlap.

Overstep or Transgression.—This should be distinguished from overlap because it is a relation between two rock-groups which are in unconformable succession; overlap being a relation between two groups which are in conformable succession. Overstep may be defined as the transgression or continuous extension of a single bed, or group of beds, across the outcrops of an older series of beds. It occurs when the older series has been tilted, so as to dip steadily in one direction before the deposition of the newer group. It is, therefore, a case of unconformity, and may or may not be accompanied by overlap.

Thus in fig. 183 the upper series as a whole oversteps successive members of the lower series, passing over the basset surfaces of *e d c b*, so as ultimately to rest on *a*. The fact of overstep is perhaps more clearly seen in fig. 182, where the basement bed of the upper series passes across or oversteps the basset surfaces of the beds, *t s p*, so as to rest on the bed, *o*. In this case there is no overlap, while in fig. 183 the upper series is an overlapping one, and the student will see the difference by comparison. *Overlap* is a relation between two members of one conformable series or system; *overstep* is a relation between the base of one series, and two or more members of an older series.

Instances of Contemporaneous Erosion.—The subaqueous erosion of a bed can only be effected by currents, and a surface which displays such channels and hollows must therefore have been brought within the influence of currents which only act powerfully in comparatively shallow water. Erosion of this kind is consequently an indication of shallow water.

Trough-like hollows are sometimes met with in coal-mining, portions of the coal-seams having been removed and the spaces filled up with clay, shale, or sandstone; the infilling material being usually the same as that which forms the roof of the coal elsewhere. Mr. Buddle has described an instance occurring in the Forest of Dean,

where the miners gave the name of *the horse* to the material which thus seemed to come down and press out the coal. This trough was found to branch when traced over a considerable area, and to assume all the appearance of having been formed by a little stream with small tributaries falling into it; the channels of the stream being afterwards filled up by the subsequently deposited materials which were spread over the whole coal.

In other parts of the country, similar interruptions to the continuity of a coal-seam are called *rock-faults,* though of course they have nothing to do with any kind of fault in the geological sense of the term. Fig. 184 represents an instance which occurred in a coal-seam at Coleorton, Leicestershire.[1] It is part of a channel excavated in the main coal, C, which is here about eight feet thick, and subse-

C  S

Fig. 184. Rock Fault, or Contemporaneous Erosion of a Coal-seam.
C, Main coal. S, Sandstone.
Length of section about 15 yards.

quently filled up with the sandstone, S. The component layers of the sandstone are very irregular and obliquely laminated, another result of current action (see p. 384), which is of course very likely to occur in cases of contemporaneous erosion.

Fig. 185 is an instance observed and described by Mr. J. Shipman, near Nottingham.[2] It will be noticed that the pebble-beds, *a,* have been eroded into hollows and ridges before the deposition of the white sands, *b,* which are exceedingly variable in their thickness, because they rest on this uneven surface and have themselves suffered erosion before or during the deposition of the conglomerate which overlies them. This conglomerate passes up into the soft

[1] See "Geology of the Leicestershire Coal-field," by E. Hull, p. 54.

[2] Quoted by Aveline, "Geology of the Country round Nottingham," p. 28.

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place. There is a marked plane of erosion between the two series, and the upper one has a layer of ironstone nodules at its base (see fig. 186), yet the general strike of the beds is the same, and there is no proof that a land surface existed in the interval.

The break between the two members of the Cretaceous system known as the Gault and the Cambridge Greensand is another instance. This almost amounts to an unconformity, for it extends over an area that is fifty miles in length, and the Cambridge Greensand or "nodule-bed," which rests on an eroded surface of the Gault, contains the riddlings of beds, which are about 100 feet thick in Bucks; still there is no difference of strike, and no evidence that

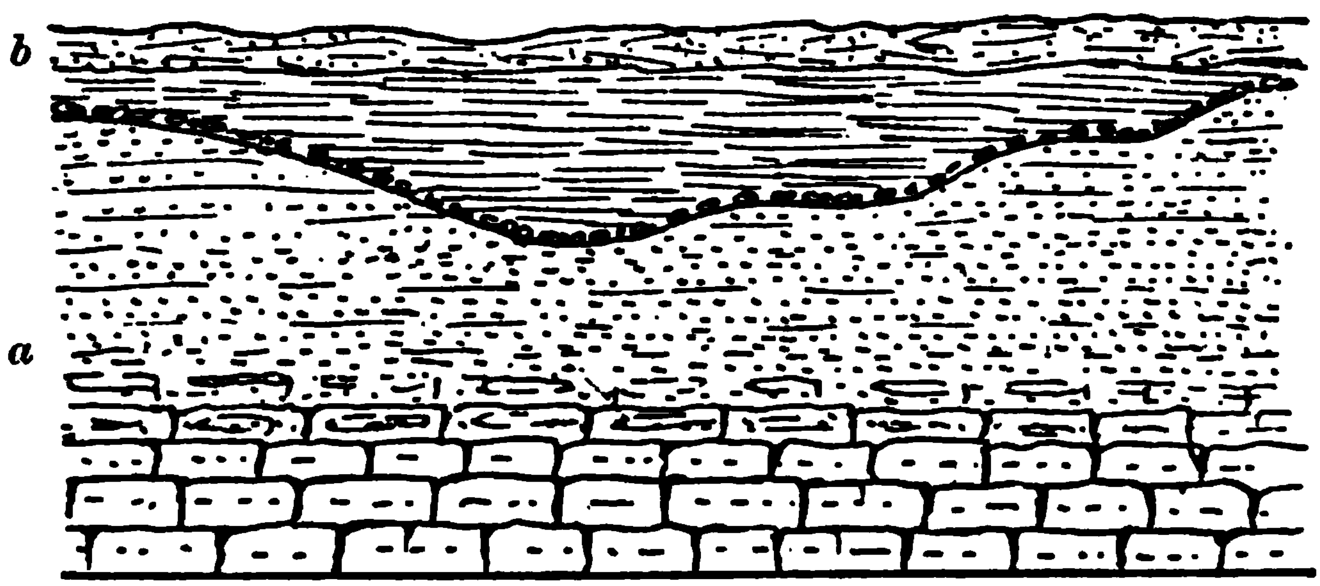


Fig. 186. Contemporaneous Erosion of Northampton Sands.
a, Northampton Sands. *b*, Clays of the Great Oolite.

the surface of the Gault was acted on by any other agent than marine currents. It is really a case of contemporaneous erosion on a large scale, for we know that what happened was this; that after the formation of the Gault and while certain beds called the Upper Greensand were being deposited elsewhere, the area now covered by the Cambridge Greensand was washed by a strong current which destroyed the upper part of the Gault, carrying away the muddy portion and leaving only the sand and heavy nodules or "coprolites" to form a basement bed to the chalk when subsidence diverted the current, or depressed the sea-floor below the limit of its action.

Instances of Unconformity.—1. *South of Ireland.*

—We have already had occasion to mention the three great groups of rock which enter into the structure of the south of Ireland (see p. 434), viz., 1, the Ordovician; 2, the Old Red Sandstone; 3, the Carboniferous Limestone. Between the first and second of these there is a wide unconformity; but the third is always conformable to the second, though it often overlaps it, in consequence of the small area within which the sandstone was deposited, the Carboniferous limestone having a much wider extension.

Fig. 187 is a diagrammatic section across Freagh Hill, a few miles north of Thomastown, in the county of Kilkenny. The Ordovician rocks, s s, were disturbed and contorted, upheaved and denuded, and lastly a level surface of planation was formed across their edges during their depression beneath the sea. Upon this surface the Old Red Sandstone was *unconformably* deposited, succeeded

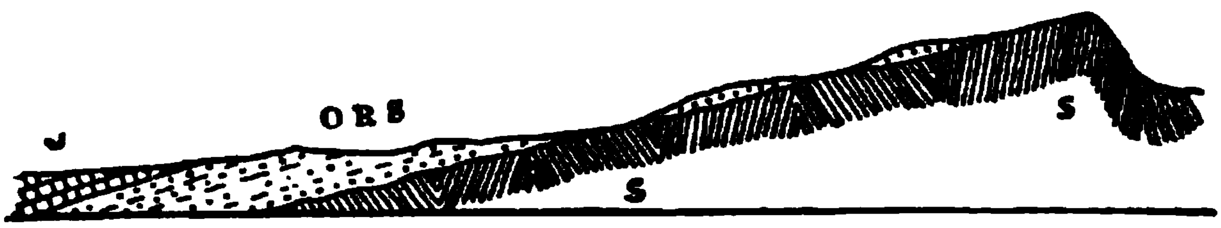


Fig. 187. Section through Freagh Hill (after Jukes).
S, Ordovician. O R S, Old Red Sandstone. C, Carboniferous Limestone.

conformably by the beds of the Carboniferous limestone. Subsequent elevation and denudation has removed all the limestone from the high ground, and also the red sandstone, except one or two patches of it, which now form outliers, and has thus re-exposed the level floor of the older rocks on which the sandstones were deposited.

The boundaries of the Carboniferous limestone and Old Red Sandstone may be followed through the counties of Kilkenny and Carlow, affording the most convincing proof of the great denudation of the Ordovician tract, which took place prior to and during the formation of the Old Red Sandstone, even to the extent of laying bare the granite which lay beneath these older rocks. The continued depression of this old land surface, the subsequent overlap of the Carboniferous limestone, and its deposition on the bare granite, are also demonstrated by the mapping of county Kilkenny.

"Fig. 188 is a diagrammatic section taken a few miles south of Thomastown, where the ancient denudation had laid bare a portion of the granite above mentioned.[1] The Ordovician rocks are traversed by granite veins in this locality, and are, near the granite, altered into micaceous schist. The Old Red Sandstone, on the other hand, rests upon the granite quite undisturbedly; it is unaltered by that rock, and is obviously made chiefly of granite sand, containing occasionally some granite pebbles, though not so many of those as fragments of the slate rocks, when it rests upon them. The granite is now readily decomposed and easily crumbles into sand, and did so, apparently, quite as easily at the time the Old Red Sandstone was deposited upon it."

Further north in county Carlow, the sandstone gradually thins out and allows the limestone to rest directly on

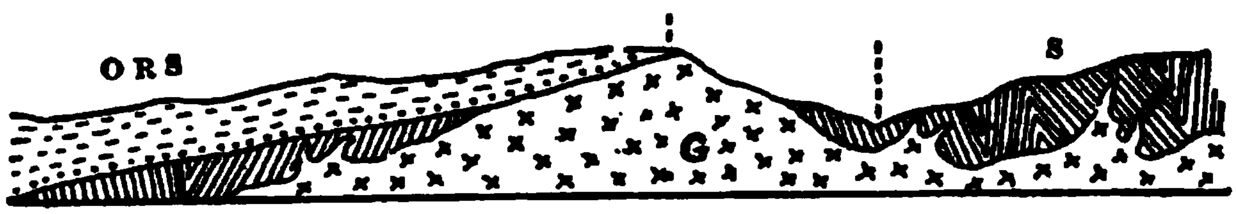


Fig. 188. Section near Thomastown, Kilkenny (after Jukes).
G, Granite. S, Ordovician. O R S, Old Red Sandstone.

the surface of the granite. The beds of limestone dip gently from the granite, but are not altered by it, and were evidently deposited in the sea upon a bare floor of granite, just as beds might now be deposited upon it if the country were again depressed beneath the sea.[2]

2. *Gloucestershire.*—The relative position of the newer and older rocks round the Bristol coal-field affords another excellent instance of unconformity. The older series, consisting of the Devonian Rocks, Carboniferous limestone, and Coal-measures, are thrown into a broad periclinal basin, the uppermost series of coal-measures lying in the centre of this basin (see fig. 189); but these older rocks are unconformably overlaid by a much newer series, consisting of

[1] The relations of this granite to the surrounding rocks have been described in Chapter X.

[2] Condensed from the account given in Jukes' "Manual of Geology."

red sandstones and marls (Trias), dark clays (Lias), and oolitic limestone (Inferior Oolite), which lie nearly horizontally, and are spread over the edges of the carboniferous series, so as to conceal their outcrops in the manner indicated in fig. 189.

The figure is a generalized section through that part of the coal-field which lies to the N.E. of Bristol, and the faults which traverse the older rocks are not there very numerous or important; in other parts of the district there are a number of faults which break the continuity of the older strata, but do not extend through the newer rocks. Hence it is evident that the older series had been bent into folds and basins, fractured by faulting, worn down and denuded by detritive agencies, and finally planed down to a tolerably level surface by marine erosion, before the deposition of the newer series of deposits.

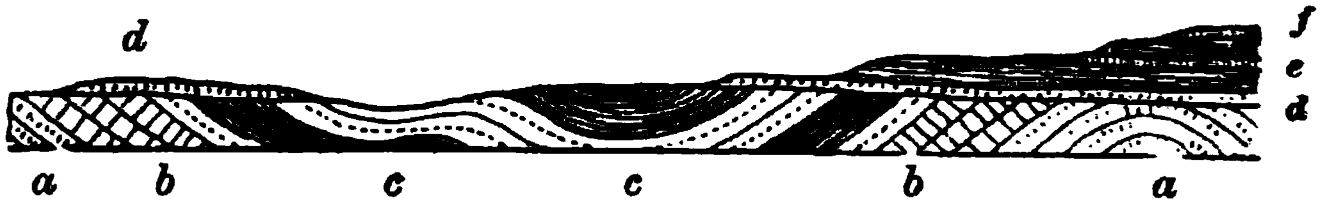


Fig. 189. Diagram Section across the Bristol Coal-field.
a, Devonian Rocks. *b*, Carboniferous Limestone. *c*, Coal-measures. *d*, Trias. *e*, Lias. *f*, Oolite.

Comparative Magnitude of Unconformities.—The examples given in figs. 187, 188, and 189 are cases of very strong unconformities, the older rocks in each case having been greatly disturbed and indurated before they were covered by the newer series, and the gap between them representing a long period of time during which many thousand feet of strata were accumulated in other parts of the British region.

The case illustrated diagrammatically in fig. 183 is an unconformity of much less magnitude; the disturbance of the lower series was not great, and the plane of erosion does not indicate the lapse of a very long period. The magnitude of the break is of course greater at the western than at the eastern end, but if we take it at the point above the letter *b* it is measurable by only a few hundred feet of strata.

The reader will remember, therefore, that the strength

or magnitude of an unconformity is a variable quantity, depending on the amount of terrestrial disturbance and subaerial erosion which took place in the interval represented by the physical break. This is *indicated* by the extent to which the older rocks were tilted, faulted, flexed and altered before they were covered by the newer strata, and it is *measured* by the thickness of the deposits which resulted from their erosion, and were laid down in neighbouring areas.

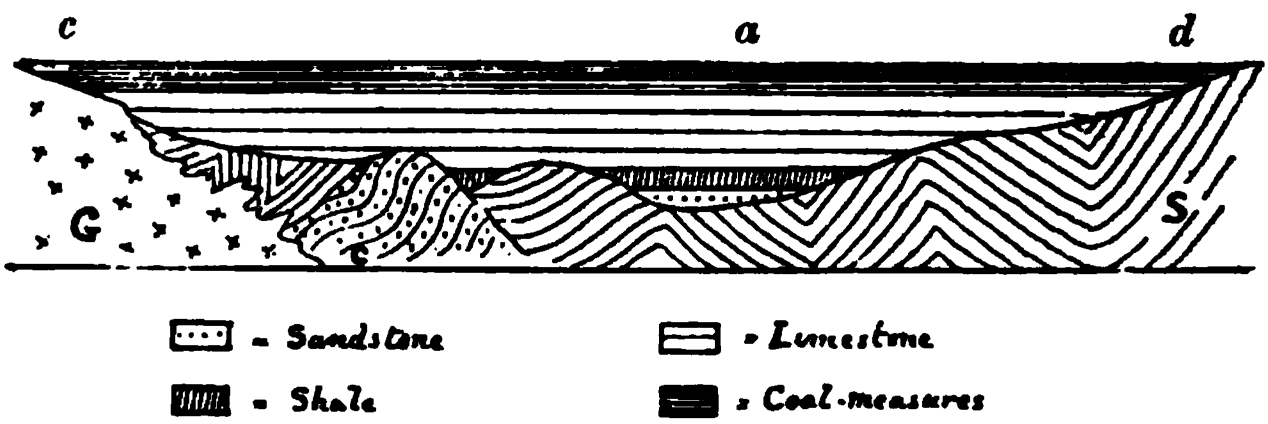
Instances of Overlap.—An excellent instance of overlap is to be found in the south-west of England, where the lower members of the Cretaceous series are successively overlapped by the upper members, as traced from east to west. This overlap is represented diagrammatically in fig. 183. The several groups of which this series is composed in the Isle of Wight have already been mentioned (see p. 420), and they are all to be found near Swanage, on the coast of Dorset, but when traced westward through this county by means of the sections exposed in the numerous coves described on p. 167, the Wealden beds become thinner and thinner, and are ultimately overlapped by the Lower greensand. Further west this, in its turn, disappears, and allows the attenuated representative of the Gault to rest directly on the Lias clays below near Lyme Regis. Beyond this point the Gault itself cannot be traced, for it becomes sandy, and is indistinguishable from the Upper greensand which continues below the chalk as far as the latter is traceable. As already stated, the overlapping strata in this instance also overstep successive members of the Jurassic series in consequence of their dipping in the same direction. The same transgression or overstep is plainly visible on a geological map of Yorkshire, where the chalk passes across the basset surfaces of several members of the Jurassic system.

A good example of overlap is found in the county of Dublin, and has been fully described by Professor Jukes, from whose account the following is condensed. The rock-groups which occur in this county may be grouped into two great series—an upper and a lower,—the granite being included with the latter, because it was intruded

into those rocks before the deposition of the upper series:—

Lower Series.	Ordovician, Cambrian, Granite.	Upper Series.	Coal-measures, Carboniferous lime-stone, Old red sandstone.

If the reader will refer to sheets 102 and 112 of the "Geological Survey of Ireland," where the surface exposures of the different rock-groups are indicated by different colours, and to the section, fig. 190, he will see that the beds of the upper series, taken as a whole, rest in different places on different parts of the lower series, and upon the granite. The upper rocks, therefore, are completely unconformable to the lower. These lower rocks rise to the



G, Granite. C, Cambrian. S, Ordovician.

Fig. 190. Diagram section across County Dublin.

surface in four separate localities—1, in the hills south of Dublin; 2, at the hill of Howth; 3, on the coast near Portraine; 4, in the district west of Skerries.

The next thing that would strike us is that, although there are so many miles of boundary to the rocks of the upper series, yet the basement beds of that series—viz., the Old Red Sandstone and the limestone shale—are only found at one locality, and that near the centre of the district (Portraine). No evidence of the existence of these basement beds was discovered, either along the southern or the northern border of the great limestone tract.

All these facts are only explicable on the principle of overlap in the following way:—Before the deposition of the upper series, the lower group must have formed an exten-

sive area of dry land, with a widely denuded and irregular surface, as suggested in fig. 190, which was produced in the same way as such surfaces are now produced, viz., by the action of rain and rivers.

Eventually a movement of depression set in, and this dry land was gradually submerged beneath the neighbouring sea. The first portion of the area which was brought below the level of the water was the part about Portraine (below *a*, in fig. 190), either because it was depressed more rapidly, or because it was lower than the other parts of the country. Certain beds of sand, now forming the Old Red Sandstone of that locality, were accumulated there, and certain beds of black shale, forming the Lower Limestone shale, were deposited over them as the depression continued, These beds did not extend far to the north or south of that locality, simply because the water ended against the shore, within a short distance of it. As the land, however, continued to sink, the water extended farther and farther over it; and the beds deposited in that water acquired, in like manner, a wider and wider extension, and altogether overlapped those beneath them, as represented in fig. 190. It is probable that, as a final result, horizontal beds of coal-measures were spread over the whole area, resting upon the granite of the Wicklow hills on the south, and upon the hills of Meath on the north, and completely concealing all the limestone below. Patches of these coal-measures are only now to be found in the northern part of the district, having been removed from all other parts by the detrition which has produced the present denuded surface.

After all the beds were laid down in the manner indicated, a movement of elevation took place with its concomitant results of tilting, contortion, and fracture. The formation of a second land-surface, with its resultant denudation, brought to light the lower beds in different places according to circumstances, and re-exposed portions of that still older land-surface which had been covered up by the deposition of the Carboniferous rocks.

It is not always that the fact of overlap can be so easily detected, and the relative age and superposition of the overlapping beds so easily ascertained. Let us suppose that

circumstances had been favourable for the formation of sandstones over the whole surface of the sinking land, and not only at one locality: sand and shingle beaches might have been formed continuously along the sea margin as the land sank, as the coasts receded, and as the sea gradually spread over a wider area. If this had happened, sandstones and conglomerates would be found resting on the old rocks under the points *c*, *d*, as well as under *a*, they would pass laterally into shale and limestone in the manner indicated previously on p. 381, and they would also be succeeded vertically by shale and limestone as the submergence became deeper and deeper. Such cases frequently occur, and are liable to lead the observer astray, unless he bear in mind that the sandstones, etc., which might exist under the points *c* and *d* would not be continuous and coeval with those under *a*, but were contemporaneous with the formation of pure limestone in the central part of the area. The first-formed beds under *a* would be the true basement beds of the series, but the last-formed beds would belong to the upper portion of the series, and would have to be considered as part of the coal-measures. If, however, the whole series subsequently came to be elevated again into land, tilted, contorted, fractured, and denuded, geologists who were not on their guard might easily suppose a succession of sandstones, shales, and limestones occurring always in the same order, and with similar characters, and belonging certainly to the same system of beds, to be separate successive parts of the series.

Practical Importance of the Subject.—The phenomena of Unconformity and Overlap, and the conclusions to which they lead us, have their practical as well as their theoretical interest; and the whole subject ought especially to be thoroughly understood by those who are engaged in searching for minerals which occur in one set of rocks, and can only be reached by boring through beds belonging to another set. The success of such borings depends in many cases upon the conformity or unconformity of the two sets of rocks; and the probable thickness of the upper set may be miscalculated unless the possible existence of overlap is taken into account.

Thus in county Antrim, where the Trias or New Red

Sandstone rests on the Carboniferous rocks, there has long been a feeling that it is only necessary to sink through the sandstones in order to find the coal-measures. Since, however, the one lies unconformably upon the other, it follows that though in one locality the Trias may rest upon coal-measures, in other places it may lie upon any of the beds which come out from beneath the coal-measures; and from the structure of the district it appears that the chances are something like twenty to one against the coal-measures being found under any particular spot of the Trias.

The same is the case in the central districts of England, where the Coal-measures rest unconformably upon Silurian rocks, and are themselves unconformably overlaid by newer deposits of sandstone and conglomerate. Explorations in search of coal are from time to time undertaken in this district, and it is of the highest practical importance that the explorers should have a complete comprehension of the nature of these discordances, and of the possible consequences which they involve. Such knowledge is indeed absolutely necessary to avoid the fruitless expenditure of large sums of money. Many thousands of pounds have been thrown away, in this central part of England alone, in abortive attempts to discover coal, the expenditure of which nothing but the most complete ignorance of geology could have rendered possible.

Again, in the Bristol and Somerset coal-fields, which are so largely covered by newer deposits that rest unconformably upon the older rocks, although coal has been worked in many places beneath the Triassic sandstones, it does not by any means follow that coal-seams will always be found below these sandstones. If a boring were made at the foot of the Cotteswold hills in the expectation of finding coal, the undertaking would in all probability prove fruitless; the bore would pass through the lias clays and Triassic sandstones, and would then enter either the Carboniferous limestone, or the still older rocks below it, as indicated in fig. 189.

It will be noticed, however, that in this figure an anticlinal axis is represented beneath the Cotteswold hills; this is hypothetical, but is considered to be a very probable occurrence, so that still further east the coal-measures may

roll in again and form another basin beneath the newer rocks. As a matter of fact the coal-measures have been reached at a depth of about 1,000 feet below the surface at Burford in Oxfordshire, and it is quite possible that several such buried coal-fields may exist under the country between Bristol and London.

Recent borings in London, and at other places in Middlesex and Hertfordshire, have shown that the newer beds (chalk, etc.) rest unconformably upon a broad ridge of older rocks, comprising the Silurian, Devonian, and Carboniferous series, which appear to have a general dip to the south, and that by this southerly dip coal-measures which overlie the carboniferous limestone may be brought in to the south of London, and may underlie parts of Surrey.

The considerations above mentioned will be sufficient to demonstrate the great practical importance of an unconformity between two series of rocks.

PART III.

PHYSIOGRAPHICAL GEOLOGY.

THE first chapter of this book treated of the earth as a whole, and the opinions entertained with regard to the general structure of its mass and the condition of its interior were there given. In the chapters of Part II. the structure and arrangement of the rock-masses which compose the superficial portion of the earth's crust were described. We are now in a position to deal with the problems of Physiographical Geology, or that branch of the science which seeks to account for the existence of the varied physical features of the earth's surface, and to explain the manner in which hills and valleys, plains and table-lands, continents and mountain chains, have been gradually developed by the operation of the physical forces which act within or upon the crust of the earth.

CHAPTER I.

LAND-SCULPTURE, OR THE EVOLUTION OF SURFACE-FEATURES BY THE PROCESS OF EROSION.

IN Part I., Chapters VI., VII., VIII., we described the action of the various agencies which are continually engaged in the work of erosion and denudation; but their operations were treated rather from a detritive point of view, as resulting in the collection of materials for the formation of new rocks, than as leading to the production of new physical features.

It is clear, however, that agencies which sweep away so much rock from the land must in time cause very great changes in its physical features and contours. An elevated table-land, for instance, by the unequal disintegration of its surface, and by the erosion of valleys out of its mass, may gradually be converted into a series of hill ranges more or less isolated from one another. Such a process is fitly termed *Land-sculpture,* as analogous to the work of a sculptor, who carves effigies out of solid blocks of stone.

Many persons express surprise that the formation of such prominent features as lofty hills and profound valleys should be attributed to such comparatively feeble agencies as those above mentioned; but it must be borne in mind that we are naturally apt to underrate the amount of work done by these erosive agencies, because we see that in any period of time during which we can observe their action the results produced are very small. On the other hand, when we look at the magnitude of the results which have been produced in past time, we are liable to suppose that the agencies which have operated in former times were much

more powerful and destructive than those which are now in action around us. "When, however, we come to reason on the matter, we find it very difficult to imagine what these agencies could have been if they were altogether different from 'existing causes'; and equally difficult to suppose that existing agencies have ever acted with much greater intensity than at present, unless we assume the general physical laws of the world to have been different from what they are now" (Jukes).

We shall therefore take it for granted, in accordance with the tenets of the Lyellian philosophy, that all the geological phenomena observable among stratified rocks are due to the same causes as those now acting in some part of the world, or to some modification and combination of these causes, such as we may reasonably suppose to have occurred in the course of the earth's history.

To such seemingly insignificant and slowly acting causes, operating continually through long periods of time, must be attributed all the erosion of rock which gives to elevated land its cliffs and precipices, its hills and valleys, and all the varied features of the earth's surface.

Share taken by different Agencies.—The detritive and erosive agencies already described may be grouped under two heads, according to differences in their mode of operation, and in the results of their action.

1. Marine agencies, which act along the margin of the land, and tend to produce an approximate level surface or plain.

2. Subaerial agencies, which act over the whole surface of the land, and tend to produce a system of valleys and watersheds, hollows and relative eminences.

Few parts of the sea-bottom could be raised into dry land without passing through the destructive plane of the sea-level, and no part of the land could be submerged without passing through the same plane, and being exposed for a shorter or longer period to the erosive action of the waves. These agents would wear down the inequalities of its surface and would produce an inclined plane, the extent and inclination of which would depend on the slope of the sinking or rising land, and the rate at which the movement took place. It must be remembered,

too, that a tract of land which has been submerged and then upraised must have been twice subjected to this levelling process, and on its second emergence would present a wide area with a nearly level or slightly undulating surface. Such an area has been termed a *plain of marine erosion*, but would perhaps be more aptly called a *surface of planation*. When once any such tract had been brought almost up to the sea-level, only a very slight further uplift would be required to raise a large area of it through that level, and cause it to become dry land, so that there would be no time or opportunity for the formation of cliffs. Slight irregularities there doubtless would be, and indeed it must be understood that the words *plain* and *planation* are used in a general sense to convey the idea of a surface where the vertical height of any inequality is small as compared with the horizontal extent of the area.

As soon as this surface produced by marine erosion is elevated into dry land, it is subjected to the detritive action of the subaerial agencies already described, and is ultimately carved out into new forms of hill and valley. In the present chapter we propose to describe the manner in which these features are developed. Regarded as *corradents*, or agents of land-sculpture, the subaerial agencies act in two different ways; the atmospheric agencies, rain, frost, sun, and wind, act generally upon rock-surfaces, wearing away some parts faster than others, and so developing those which best resist their action into ridges and eminences. Running water, on the other hand, acts along certain lines, and excavates channels into which rain carries the material worn from the wasting surfaces. The original course of these channels is determined partly by the slope of the surface over which the water commenced to run, and partly by other conditions to be mentioned presently.

Formation of Valley Systems.—The manner in which rills of water tend to unite and form a connected series or river system which impresses itself on the surface of the country as a valley-system, is well exemplified by the drainage of a sand or mud-flat at low tide, which has been graphically described as follows:[1] "If we watch the

[1] Jukes, "Manual of Geology," second edition, p. 103.

tide receding from a flat muddy coast, we see that the mud flat, even where no fresh water drains over it from the land, is frequently traversed by a number of little branching systems of channels, opening one into the other, and tending to one general embouchure on the margin of the mud flat, at low-water mark. The surface of the mud is not a geometrical plane, but slightly undulating; and the sea, as it recedes, carries off some of the lighter and looser surface-matter from some parts, thus making additional hollows, and forming and giving directions to currents, which acquire more and more force, and are drawn into narrower limits as the water falls. Deeper channels are thus eroded, and canals supplied for the drainage of the whole surface. First two, and then more, of these little systems of drainage unite, until at dead low-water we often have the miniature representation of the river system of a great continent (wanting, of course, the mountain chains) produced before our eyes in the course of a single tide, in the very manner and by the very agent by which all river systems on all islands and continents have been produced. The difference between them is this only, that our islands and continents are now above the sea, not in consequence of the gradual fall of the water, but in consequence of the gradual rise of the land."

A land surface does not of course exactly correspond with the conditions of a sand-flat, it does not generally consist of one kind of material, and it does not always slope steadily in one direction; there is usually some main ridge or water-shed from which the water is thrown off in different directions. Let us suppose a land commencing to rise above the sea, the ridge of what may eventually become a range of mountains being the first part to become dry land. As soon as this tract of dry land is established above the reach of the waves, rain and rivers commence their work of erosion and excavation, beginning first upon the ridge, and extending to each piece of lower ground as it is laid dry. It is easy to see that the first rain streams formed on the rising ridge would run directly off down the slopes from the crest into the sea. These would begin to form the transverse valleys of the range. As soon as they became a little deep, other small streams would flow into

them from their sides; and these, acting on any softer or more easily destructible bands of rock, would begin to excavate tributary valleys which would extend themselves laterally on either side of the primary or transverse valley, and would receive the drainage of a certain section of the region. As the land rose on each side of the ridge, the streams would extend their channels over it, and some would run together and form rivers.

If the rainfall was everywhere the same, if the region consisted of only one kind of rock, and if this rock was composed of a succession of horizontal beds, the resulting system of rivers and watersheds would be very symmetrical; but since most countries consist of many different kinds of rocks, the beds of which are tilted in different directions, and the rainfall varies at different places, it follows that some streams are able to work more rapidly than others, and so the relative areas of the drainage basins come to be very unequal.

Conditions which determine the Position of Hills and Valleys.—The initial courses of the streams, and the general contour of the ground, will depend on the following circumstances:—

1. The original slope of the surface.
2. The disposition and lie of the stratified beds.
3. The relative resistant power of the rocks, depending partly on their hardness, and partly on their chemical composition.
4. The presence or absence of igneous rocks.
5. The direction of any strong divisional planes, such as those of bedding, jointing, cleavage, or faults.

Of these conditions, the second is perhaps the most important, so much depending upon whether the beds are horizontal, inclined, or curved, that it will be instructive to consider each of these three cases separately.

A. *Erosion of Horizontal Strata.*—The simplest case which can be imagined is that of the elevation of broad and level tracts of country, in which the strata are for the most part nearly horizontal. In such a case the greater part of the surface would be occupied by one or two kinds of rock, and the resultant features would depend chiefly upon the manner in which these crumbled down under the action

of erosive agencies. Fig. 191 illustrates the forms into which horizontal strata of sandstone, shale, and limestone may be carved. The sandstone which formed the original surface, S P, has been cut through, and portions only are left to form the flat-topped ridges which separate the valleys. These valleys will be wide, with long gentle slopes where the sides consist of clay, but will have a narrow gorge or canon at the bottom, if the stream has trenched the underlying limestone.

Such cases are rare in Europe, but excellent instances are to be found in eastern Egypt and in the western and central parts of North America. The forms produced by the action of rain and wind upon the horizontal strata of these regions, and the excavation of profound ravines or canons by the rivers which traverse them, have already

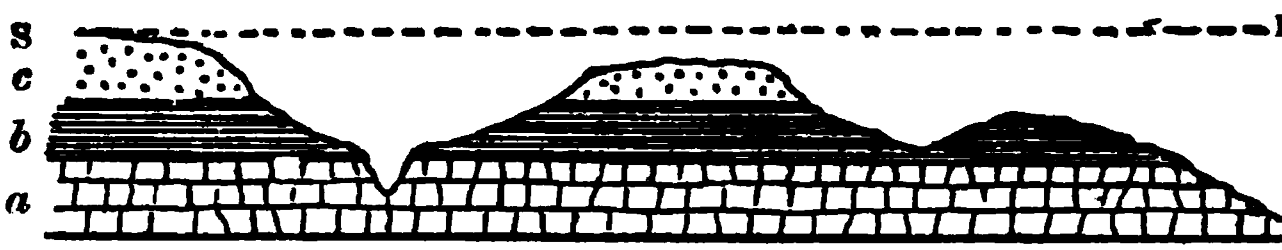


Fig. 191. Erosion of horizontal Beds.
a, Limestone. *b*, Shale. *c*, Sandstone.

been described; but the combined effect of all the different detritive and erosive agents in Colorado and Utah is to produce an amount of sculpturing and a diversity of outline which is truly wonderful. Dr. Geikie has given an excellent picture of the peculiar scenery of the Uinta Mountains in the following terms: [1]—

"The world can show few more impressive memorials of the efficacy of subaerial erosion than the Uinta Mountains. There are no structureless crystalline rocks here to deceive us with their ruggedness. Wherever the eye turns it detects the same long lines of horizontal stratification that serve as a base from which the reality and amount of the erosion may be measured. . . . Originally the rocks stretched in an unbroken sheet across the mountains; but in the course of ages this continuous mantle has been enormously eroded. Deep and wide valleys, vast amphitheatres, lofty terraced

[1] "Geological Sketches," Macmillan, 1882, p. 229.

alcoves, and profound gorges, fretted with an infinite array of peaks, buttresses, pinnacles, columns, obelisks, and endless forms which defy the observer to find properly descriptive names for them, have gradually been carved out of these rocks. To gain such a vivid impression of the importance of subaerial waste in the evolution of mountain forms was worth all the long journey in itself." Views and descriptions of this scenery will be found in Captain Dutton's "History of the Canon Region of Colorado" (U.S. Survey Monograph).

B. *Erosion of Inclined Strata.*—Next let us suppose the case of a slightly inclined area of planation, consisting of different strata dipping constantly in one direction, so that their outcropping edges form broad bands stretching across the surface. In this case the surface features developed by denudation will depend upon the comparative destructi-

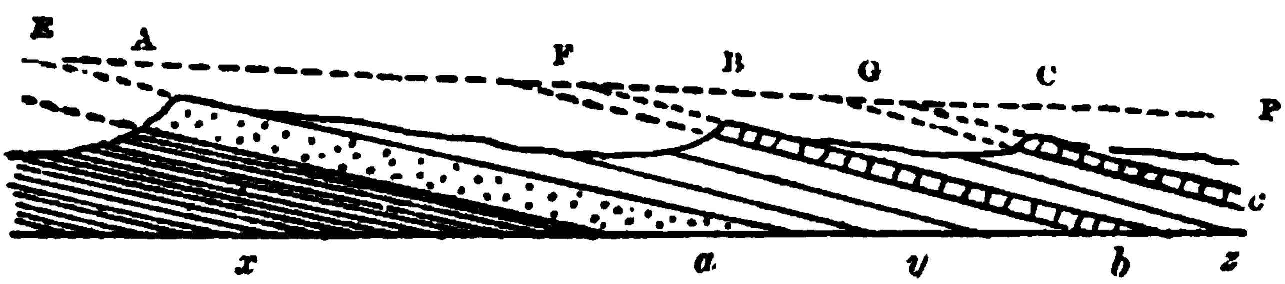


Fig. 192. Erosion of inclined Strata.

bility of the different rocks. Where hard and soft beds alternate with one another, as so frequently happens, the softer bands will be worn away more rapidly than the harder, and the surface will be sculptured into a series of alternate ridges and hollows, with long gentle slopes in the direction of the dip, and steeper slopes across the outcrop of the hard beds. These steep slopes are called *escarpments*, and their general direction coincides with that of the strike. In fig. 192, S P is the original surface of planation, *a b c* are beds of hard rock, and A B C are the escarpments gradually developed by the detrition of the strata, *x y z*. The broken lines show the original prolongation of the beds, and the extent to which the escarpments have receded.

It sometimes happens that the sloping upper surface of a hard, durable bed is completely denuded of its covering by the atmospheric agencies, so that the slope of the ground coincides for some distance with the sloping surface of the

inclined stratum (see fig. 192). Such a surface is called a *dip slope*, while the opposite slope may be termed the *scarp slope*.

The way in which these peculiar and characteristic features are developed, appears to be as follows:—The first lines of drainage established on the area of planation would form transverse valleys across the slope, from S to P, with longitudinal tributaries along the strike of the beds. The transverse streams would cut through hard and soft beds alike, down to a certain base level of erosion, and the depth of their valleys in the soft beds would necessarily depend on the depth of the ravines which they could excavate through the hard beds. Rain falling on the tracts of ground that lie between these transverse valleys will develop the outcrops of the hard beds into banks or ridges by washing away the softer strata on each side. The ridges so developed will form the natural limits or watersheds between the longitudinal valleys, and as the streams deepen these valleys the height of the ridges or escarpments will be increased.

The channels of the longitudinal streams could not, however, be deepened below the level of the point where they join the main river; each tributary, therefore, will have its base line of erosion limited by the depth of the main valley, and when the limit of vertical erosion has been reached, the stream will be chiefly occupied in carrying off the material washed into it by the rain, and the whole process of valley and scarp-making will come to a standstill.

In the first instance, there might have been many streams running either directly or obliquely across the beds which subsequently became escarpments, while the lateral tributaries may have been small and short; but as the ridges developed themselves and the interspaces were lowered by detrition some of the obliquely crossing streams would be diverted into the lateral tributaries of the more powerful transverse streams.

The long slope behind each escarpment is the result of the original tendency of the water to run in that direction till checked by the rise of the opposite scarp-slope; thus the rivulets flowing in the direction of the dip will generally be

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that the escarpments intersected at the points A B C must have started from the lines intersected at E F G, and have receded to their present positions. This recession will go on as long as the valleys are being deepened, but will not be continued indefinitely.

The outline of the edge or border of the escarpment depends partly upon the relative share taken by the agencies above mentioned, and partly on the inclination of the strata by which it is formed. Sometimes an escarpment forms a continuous and uninterrupted ridge, running in a nearly straight line for a considerable distance; sometimes its edge is furrowed by watercourses, and hollowed out into a succession of deep embayments, with intervening spurs and promontories that form more or less isolated hills. The sinuosity of its outline generally depends upon the presence or absence of strong springs, and the local landslips to which they give rise.

This difference is well illustrated by the two great escarpments which run through Lincolnshire. Of these, the more westerly is known as the "Lincolnshire cliff," and forms a remarkably straight ridge, running nearly due north and south from Lincoln to the Humber, with very few sinuosities, and with little variation in height. This ridge is formed by the outcrop of the upper part of the series of clays and marlstones called the Lias, capped by the lower beds of the Lincolnshire limestone; the easterly dip of the beds, and the slight thickness of the limestone along the top of the ridge, prevent the existence of strong or numerous spring along its western slope. The easterly escarpment is that of the Chalk Wolds, which runs in an irregular line from S.E. to N.W., and consists of (1) a series of stiff clays and ironstones, succeeded by (2) coarse sand-rock and (3) red and grey chalk. The dip is very slight, and the thickness of chalk is considerable, so that strong springs are thrown out sometimes at the base of the chalk, sometimes at the base of the sand. The action of these springs has produced beautiful little hollows and recesses in the face of the scarp, some of which have been widened and extended into valleys by the rain-water draining into them from the higher ground. The edge of the Wold escarpment has consequently acquired a most irre-

gular and diversified outline, which forms a remarkable contrast to that of the "Lincolnshire cliff."

c. *Erosion of Curved Beds.*—We have next to consider the case of an area of curved or undulating beds, and the influence which such curvature exercises upon the development of its physical features.

Let the fig. 194 represent a section through such an area, and let us suppose the rocks to consist of shales and sandstones overlying limestones, and thrown into anticlinal and synclinal curves. The features usually presented by the detrition and sculpture of such an area are those indicated in the figure, namely, a series of alternate ridges and valleys, with nearly equal slopes. Usually, moreover, they have this peculiarity, that the valleys coincide with the anticlinals, and the hills with the synclinals, so that the stratigraphical troughs become orographical ridges, and

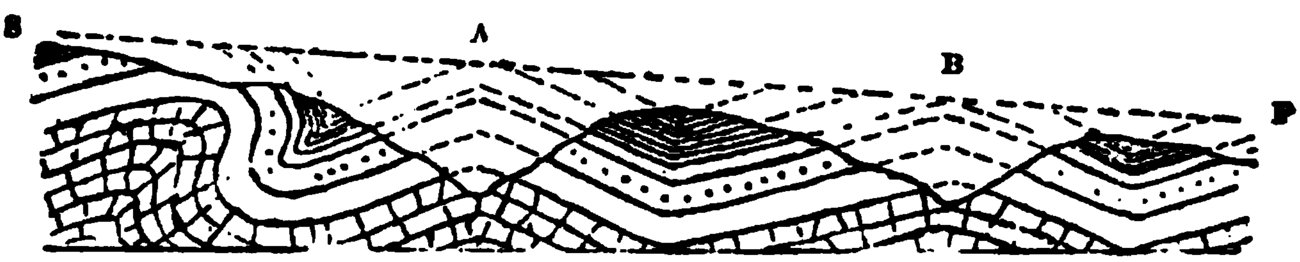

Fig. 194. Erosion of curved Beds.
P, Surface of planation. A B, Valleys coinciding with anticlinals.

vice versâ, which is the opposite of what might, at first sight, be deemed probable. This arrangement, however, is the natural result of the structural peculiarities imparted to the rocks by curvature, and the consequent increase or decrease of their liability to mechanical erosion. Where the strata have been bent into broad anticlinals, their coherence is weakened, because they have been subjected to tension; while in the synclinals, they have been subjected to compression, and consequently their coherence is increased. Lastly, where they have been thrown into sharp curves and contortions, they have generally been more or less compacted and indurated.

Thus, when the first stream courses were established over such an area, the main rivers would flow from S towards P, and the compacted rocks near S would remain as high ground. Of the tributary streams, running more or less

along the strike of the beds, some would flow along the anticlinal axes, and some perhaps along the synclinal axes; let us consider which of these would be likely to excavate the deepest channels. It must be remembered (see p. 166) that where rocks are freely jointed they yield more easily along these planes than along those of bedding. Now the principal effect of tension on the rocks of the anticlinals would be to open the lines of jointing; consequently, as the stream undermined the bases of the blocks, they would slip down on both sides along the joint planes, and falling into the stream would be broken up and carried away. In the synclinals, on the other hand, the effect of compression would be to close up the joints; and, moreover, these planes being mostly vertical to the stratification, would incline away from the banks of the stream, so that the beds would not be so liable to slip down.

The drainage, therefore, will eventually be directed into the deeper channels running along the anticlinal axes, and the widening of these valleys by pluvial action will leave the synclinal axes to form ridges and ranges of hills. By a similar process of circumdetrition a *periclinal* basin will become an isolated hill.

Influence of relative resistant Power.—The relation above described as ordinarily subsisting between the flexures of the strata and the surface features of the ground holds good only when the rocks which formed the original surface of planation did not differ very greatly in their resistant power. If, however, some of them possessed greater inherent powers of resisting disintegration and detrition than their neighbours, the latter will be worn away, and the former will remain as hills, whether this result is or is not favoured by the general arrangement of the flexures. The whole process, in fact, is one of natural selection, and the development of surface inequalities out of any tract of country may be described as the result of selective and differential erosion, the power of the destructive agents being directed and modified by the capacity of the different rocks to resist them,—the softer and weaker portions of the surface being continually attacked and destroyed, while the harder and more durable portions survive the detrition and maintain their position for a longer period of time.

The law of the survival of the strongest and fittest holds good, therefore, in physiography as well as in biology, in the development of mountains as well as in the development of species.

Masses of hard crystalline rock, whether igneous or metamorphic, always form high ground, chiefly because the interlocking crystals of which they consist are less easily separated from one another by mechanical agencies than the particles of more loosely compacted rocks. Bosses of intrusive igneous rock like Mynydd Mawr (fig. 158), and interbedded sheets of felstone like those of Snowdon, Aran, and Arenig (p. 498), are illustrations of this law, as are also the Malvern Hills, composed of gneissic rocks, and the Wrekin in Shropshire, composed of several crystalline rock-masses. Even moderately hard limestones form ridges and escarpments when associated with clays, shales, and sandstones. It is entirely a question of relative durability or capacity of resisting the action of rain and atmospheric agencies.

Many instances of the coincidences of the hill-ranges with anticlinal axes, when these are formed of hard arenaceous rocks, are to be found in the south of Ireland: the Commeragh, Knockmealdown, Galtee, and Macgillicuddy ranges, and the higher mountains of Kerry, Cork, and Waterford generally.[1] In these counties the hills are formed of anticlinal folds of red sandstones and slates, while the valleys lie in the synclinal curves.

In these and other cases the valleys coincide with synclinal axes, because these are occupied with beds, such as shales and limestones, which yield more easily to chemical disintegration or mechanical erosion than the rocks of the anticlinal folds. In Cork and Waterford the limestones have been worn away, in spite of their hardness, because they have less resistant power than the hard and compact sandstones which form the anticlinal ridges; for the limestones yield to chemical action, and their material is removed in solution as well as in suspension.

Other cases where valleys coincide with synclines may have arisen from the fact that on the original surface of

[1] See "Explanations of the Sheets of the Geol. Survey of Ireland."

planation the synclinal axes were occupied by shales or limestones, and the valleys excavated along these axes may sometimes have still been maintained as lines of drainage after the removal of all the shale or limestone.

Transferred Drainage.—There are cases where it is unnecessary to assume the previous existence of a plane of marine denudation in order to account for anomalies in the present system of drainage. The channels of the rivers and streams may have been originally established on the surface of some formation which has since been entirely or almost entirely removed from the area in question. Suppose, for instance, that a large area of flexed and folded rocks of various kinds is unconformably covered by a newer series, of which the highest member is a clay formation, as in fig. 195. If such an area be raised and remain for a long time as a land surface, the system of drainage formed on the

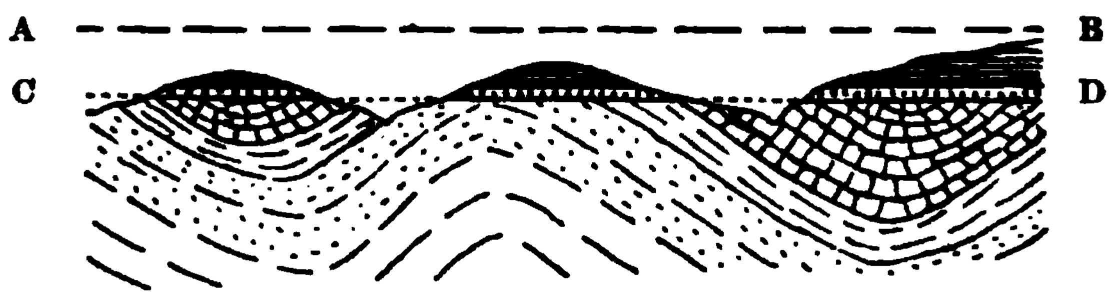

Fig. 195. A transferred Drainage System.

surface A B may be in time so deeply trenched that it sinks into the surface of the older rocks, while the newer series is reduced to the condition of isolated patches. So long as the general surface of the older series, C D, is protected by the cover, the river-courses will be engraved on it without reference to the relative hardness or the stratigraphical arrangement of the rocks composing it. In this way a river system may be *transferred* from the surface of one formation to that of another, and will be engraved on the latter in a manner which would be very difficult to understand if we did not replace in imagination the strata that formed the surface on which it was first established.

The valley of the Bristol Avon may be explained in this way, the course of the deep trench which it has cut in the Carboniferous rocks, and which forms the picturesque gorge of the Avon, having been established in the Creta-

ceous and Jurassic strata which formerly extended over the whole district. It is probable indeed that the whole drainage system of the west of England and Wales was first impressed on rocks of Secondary age, and that it has gradually sunk into the surface of the older rocks as these were laid bare by the long continued action of subaerial agencies. A similar explanation of the drainage system of the Lake District has recently been given by Mr. J. E. Marr,[1] and the process has been described by American geologists, who speak of such a drainage system as "*consequent*," in antithesis to one which is of *subsequent* formation.

Connection of Valleys with Lines of Fault.—Since the process of earth-sculpture is one of selective erosion, and the detritive agents always seize upon lines of inherent weakness, it is not surprising that valleys should sometimes coincide with lines of fault. So, also, among rocks which are well jointed, like limestones, valleys often coincide with the direction of the master-joints. The streams descending from the original watershed will naturally follow the lines of least resistance, and therefore the direction of transverse valleys may sometimes be determined by master-joints or by lines of fault. Similarly, in districts where there is no very great difference in the comparative destructibility of the rocks, the course of the tributary valleys may be guided by any lines of weakness which exist.

It is quite a mistake, however, to imagine that faults gave rise to gaping fissures which were subsequently widened into valleys by the action of streams, or to suppose that most valleys have been originated by faults because some happen to coincide with such lines of fissure. Faults only produce a definite feature at the surface of the ground, when they bring yielding and durable rocks into apposition; such a feature is due to what may be called differential detrition, and is not produced by the throw of the fault; a valley may or may not coincide with a fault under such circumstances, but if it should do so, its direction has been determined by the presence of the yielding rock, and not directly by the line of fault. Even if mural features

[1] "Geol. Mag.," Dec. 3, vol. vi. p. 150.

were produced at the time of faulting, they would in most climates be rapidly worn down and destroyed, except under the conditions above mentioned.

The inlets of a rocky coast are often due to the presence of such fissures, whether faults or joint-planes, along which the waves have worked their way more rapidly than elsewhere (see p. 166), but no one supposes that the width of the inlets bears any relation to the space between the walls of the fault or joint, or that all inlets have been formed in this manner because a few owe their origin to such lines of weakness. The relative destructibility of the rocks, and the disposition of the strata, are far more important and more general causes of differential erosion and consequently of the formation of valleys.

Breaching of Escarpments and Hill Ranges by Rivers.—It is a remarkable fact, of which England furnishes many examples, that rivers sometimes continue a direct course through a line of escarpment, when we should have expected them to have been deflected either to one side or the other along the base of the escarpment. In other cases, a river, after running for many miles along a well-marked valley, suddenly turns at right angles and passes by a deep and narrow ravine through one of the bounding ranges of hills. After the descriptions given of the manner in which parallel ranges of hills and valleys have been produced, the origin of these gaps or ravines through hills and escarpments will be easily understood; the simple fact being that the hills or escarpments did not exist when the river, which now flows through them, first began to excavate its channel. The course of the primary transverse river was determined by the slope of the original surface of planation, and it has continued to occupy the same channel during the whole process of erosion by which the longitudinal valleys were formed and the ridges developed.

This explanation was first proposed by Mr. Jukes to account for the courses of some of the rivers in the south of Ireland, and the following is condensed from his description of the valley of the Blackwater, which he selected as an illustration. "The parts of the counties of Cork and Waterford which are here adjacent to each other consist of

a number of alternate ridges and valleys, which run with great regularity almost exactly east and west for fifty or sixty miles. The hills are formed of anticlinal folds of red sandstones and slates, while the valleys are occupied by synclinal curves of thick grey limestone. The loftiest hills of the district are the Knockmealdown mountains, which rise to 2,600 feet above the sea. The lower parallel range on the south is known as the Drum ridge, and between these two ranges lies the limestone valley of Lismore, which forms a well-marked trough, both externally and internally. It runs in from Dungarvan Bay to Fermoy, a distance of forty miles, and a road might be taken the whole of that distance without ever passing over ground much more than 100 feet above the sea.

"The Blackwater river, rising in Kerry, runs for fifty miles down to Fermoy, and continues in the same straight line down the Lismore valley for about twenty miles farther, to the little town of Cappoquin.

"There, however, the river suddenly turns at right angles to its former course, and instead of following the regular east and west valley, which continues straight out to the sea at Dungarvan Bay, it cuts through the high land of the Drum ridges due south to Youghal Bay, which is, moreover, five miles farther from Cappoquin than Dungarvan Bay. Why does it take this extraordinary course? Because just to the northward of the bend are the Knockmealdown mountains, and the original river ran due south from near their summits down the slope of the original surface towards the sea. This little transverse river would be likely to receive a large rainfall, and would certainly have the most rapid course; it would, therefore, be able to keep open its original channel through the sandstone ridge while the surface of the limestone districts was sinking into longitudinal valleys, and the tributary streams were gradually increasing in length. It is evident that to whatever extent these longitudinal valleys might proceed, their streams could never cross the original transverse valley formed by the primary river. The Blackwater, as it is above Cappoquin, is one of these tributaries, but it has never crossed the primary river so as to continue down the remainder of the longitudinal valley to Dungarvan Bay,

and could never do so unless something happened to cut a channel lower down that remaining part of the valley deeper than the channel already cut to Youghal Bay."

In this, and other cases, the primary or transverse valleys are due, in the first instance, to the comparative steepness of the slope of the original flanks of the mountain range, giving an impetus to the streams, so that channels would be worn directly across all the bands of rock that run parallel to the length of the range, independently of their hardness or softness.

No stream could cut its channel in any soft band in the higher part of its course below the level of the channel in the next hard band of the lower part of its course. Its channel, however, would naturally be more narrow, and its sides more steep and precipitous, in the parts where it cut across a hard band than where it traversed a soft one. Moreover, the longitudinal valleys, originating in these soft or easily destructible bands, would be wider and more regular than the transverse valleys, and if a soft band was very wide, and continued for many miles along the length of the chain, it is quite possible that the longitudinal valley formed in it, although originally a mere tributary to the transverse valley, might ultimately be worn back along the soft band, so as to be not only wider but far longer than the upper part of the primary valley which lies above the junction of the two. The river in such a longitudinal valley would be likely to bring a greater volume of water to the point of junction than the stream in the transverse valley itself might bring. In such cases the stream running down this longitudinal valley would be very likely to be considered the main stream, although it was originally a mere tributary of the transverse valley.

The Wealden area of Kent and Sussex furnishes another excellent illustration. The structure of this district is that of a broad anticlinal curve, the arch of which has been destroyed and carried away by erosion, so that the central area now consists of a ridge surrounded by tracts of low ground which are bordered on the north, west, and south by double escarpments of chalk and greensand. Eastward, however, there is no barrier, and the coast between Eastbourne and Folkestone is low and flat, so that we should

naturally expect to find the chief rivers running eastward and having their outlets along this coast. But instead of this being the case, the principal rivers rise in the central watershed, and flow north and south, escaping to the sea through narrow valleys which breach the great chalk escarpments known as the North and South Downs. The student should not fail to inspect the geological model of the Weald exhibited in the Museum of Practical Geology (Jermyn Street).

The only explanation of these facts is a repetition of that already given: marine erosion first produced a surface of planation across the whole district while it was being slowly elevated, so that this original surface sloped gently from a central line towards the north and south. The primary streams naturally followed these slopes from the central watershed, cutting across soft and hard beds alike, and forming the transverse valleys. Their tributaries formed longitudinal valleys opening into these transverse channels, and the streams have never departed from the courses thus established upon the original surface. Thus, throughout the whole process of subsequent erosion and denudation, the Medway, the Mole, and the Wey have gradually excavated and kept open the transverse passages through the North Downs; while the Arun, the Adur, and the Ouse have in the same way formed the valleys which traverse the South Downs.

CHAPTER II.

THE INFLUENCE OF EARTH-MOVEMENTS ON THE PROCESSES OF EROSION.

IT has been stated (p. 105) that the general result of the action of the subaërial agencies of erosion is to break up and remove the materials of the land, the rain washing the resulting detritus into the streams and the streams carrying it by stages into the sea. Meantime the sea is continually attacking the more exposed parts of every coast-line, and is slowly reducing the area of every country and island which it borders or surrounds.

It is clear, therefore, that if there were no counteracting influences, if the relative level of land and sea had never been altered, and if the continents of the primeval world had remained fixed and stationary, they would long ago have been reduced to the state of shoals in a universal ocean, and surrounded with the products of their own degradation.

It is the instability of the earth's crust, resulting in all probability from the existence of a liquid substratum, that has prevented this consummation: the forces developed beneath the crust, by continually raising some portions of the crust and allowing others to subside, have maintained a certain equilibrium between the elevations and depressions of the earth's surface, and have constantly provided fresh surfaces for the detritive agencies to act upon.

It is obvious, therefore, that the power of the several agents of erosion must be greatly influenced and modified by the movements of the earth's crust. Portions of the

surface must sometimes be transferred from the sphere of one set of agencies into that of another set; agents which had gradually ceased to be operative must sometimes be given fresh scope of action; in other cases the power of agents in full operation must be gradually reduced, and when depression is carried so far as to sink a land surface deep beneath the sea, it is removed for a time from the action of all destructive agencies. As a rule, we may regard upheaval as tending to accelerate and intensify the power of such agencies, and subsidence as tending to diminish their power and to conserve the surfaces previously produced by allowing them to be buried under fresh deposits.

The influence of earth-movements in relation to the agencies of erosion is so important a factor in the production of the surface features of the earth, that it merits more definite and detailed treatment than has hitherto been accorded to it in text-books. No explanation of the physical features attributable to denudation and erosion can be regarded as complete unless this relation between the surface and subterranean forces be taken into consideration, and we propose to show its importance by specially indicating the effects of earth-movements on each of the three chief classes of erosive agents.

Influence on Atmospheric Agencies.—Most, if not all the atmospheric agencies act with greater intensity at high altitudes above the sea. It is chiefly at such altitudes that great and rapid variations of temperature occur; and in all temperate and tropical climes it is only on the mountains and high plateaux that the action of frost has much power, while in every clime rain, snow, and wind are most prevalent where the ground rises into hills and mountains.

It becomes evident, therefore, that the upheaval of a region will intensify the action of all these atmospheric agencies and accelerate the rapidity with which they do their work of disintegration. As the land rises too, a larger and larger area will be brought into the sphere of their operations.

Subsidence, on the other hand, will have just a contrary effect; it will bring portions of the hills and mountains

below the level at which such agencies are specially active; it will generally diminish the total amount of rainfall, and will allow a thicker and more protective vegetation to spread up the mountain slopes.

Influence on Fluviatile Agencies.—The effect of earth-movements in accelerating or retarding the erosive power of streams is very great. This will be the more apparent if we first consider the extent to which valley erosion can be carried in a stationary area. Let us assume a newly raised tract of country with a central plateau or tract of hilly ground from which many streams carry off the rainfall, and unite to form several rivers which run in different directions towards and into the sea. Each stream and river will continue to deepen the channel it selects until the inclination of its bed throughout its whole course

Fig. 196. Diagram of a Curve of Erosion.
A B, The slope of the river channel. S S, Sea-level.

is so lowered that the current, even after heavy rains, ceases to have any power of vertical erosion.

The slope of the channel will not be uniform, because the power of erosion depends on the velocity of the current, and this velocity is a product of the volume of water, and the declivity of the watercourse. Now every tributary increases the volume of the stream, and enables it to maintain a given velocity on a more gentle slope than before. Conversely, in ascending a river the slope of the channel *may be* greater above the junction of each tributary without increasing the velocity of the stream because the volume of water is less; in other words, the limit of erosion or corrasion may be reached on a steeper slope for every decrease in the total volume of the stream. Hence the slope to which every stream tends to reduce its channel approaches the form of a parabolic curve, the inclination

of which is constantly increasing toward the source of the stream.

The regularity of this curve is of course affected by many natural conditions, especially by the different resisting-power of the rocks over which the water runs, but if it traversed only one kind of rock, and the tributaries were nearly equidistant, there would be a near approach to a regular curve.

If we regard a river as consisting of as many lengths or sections as there are important tributaries, we may consider the volume of water passing through each section when the stream is full to be a certain average quantity, and the slope to which the current is reducing (or has reduced) its channel in that section to be an approximately straight line with a continuous fall of so many feet or inches per mile. This slope has been called by Professor Powell the *base level of erosion*,[1] but as it is not a level, the *base line of erosion* is a better term, and the curve produced by the combination of the several lengths or sections may be called *the curve of erosion* (see fig. 196).

We see, therefore, that if a region remain stationary for a sufficient length of time, the streams will reach a limit in the work of erosion, and though extraordinary floods may occasionally enable them to continue the work, the ordinary full stream will have ceased to deepen the channel through which it flows. Its force will be expended partly in the transport of detritus, and partly in the work of lateral erosion.

Let us now consider the effect which a movement of upheaval will have on such a region. It is not difficult to perceive that its general effect will be to accelerate all processes of erosion, if only because it will, as a rule, increase the rainfall on the watersheds, and by increasing the volume of water in the streams will thereby give them a greater velocity and power of erosion. Apart from this, however, the upheaval may increase not only the absolute height of the land, but the declivity or proportional slope measured in feet per mile between a given watershed and the sea; and wherever the declivity is increased the streams

[1] "Exploration of the Colorado River, 1875," p. 203.

will regain their power of vertical erosion. This result, however, must depend on the local slopes of the tract of land which has been added to the country by upheaval.

Let us suppose that the movement has been fairly rapid, and that a tract of varying width has been added to the former coast-line: in some places this tract may be so broad and flat that its general inclination is only equal to, or perhaps less, than the slope of the previously formed valleys; the river channels will then simply be continued across it, and the curve of erosion will only be prolonged without being otherwise altered. In other parts of the region, however, the slope of the newly-added tract may be greater than of the valleys which open on to it, and in this case the streams occupying those valleys will recover their excavating power, and will readjust the slope of their channels to a deeper curve of erosion. This process will

Fig. 197. Effect of Upheaval on Valley Erosion.

take place by degrees, rapids will be formed at the old mouth of the valley, and if the rocks are of unequal hardness, it is probable that a succession of rapids will eventually be produced, the site of each gradually retiring up the river and up its tributaries till every part of the valley system has been cut down to a lower base-line.

The diagram (fig. 197) will assist the reader to understand the final result of this action, as viewed along the line of the main stream or river. In this the line *a b* represents the slope of a watercourse or river-channel when the sea-level coincided with the line s^1, and the coast was at the point *b*. If now the country was raised till the sea-level came to correspond with the lower line s^2, and the slope of the newly formed land was represented by the line *b* s^2, the stream would immediately begin to deepen its channel at *b* and along the slope *b* s^2. This erosion would be carried back along the whole length of the valley until the stream had completely accommodated itself to the

altered conditions, and had deepened its channel by an amount proportional to the increased height between s^1 and s^2. The amount of rock which might be removed along the bottom of the valley is indicated by the black part of fig. 197.

If instead of being raised the region we have imagined were depressed, so that a portion of it sank below the level of the sea, the ends of the valleys in this portion would be submerged and converted into tidal estuaries, and would be partly filled with estuarine deposits; while even above the tidal influence the velocity of the streams would be lessened and erosion checked. If subsidence also diminished the amount of the rainfall on the watersheds, the velocity of the streams would be still further decreased, and they would begin to deposit their detritus sooner than they had previously done; flood plains and alluvial levels would consequently be formed throughout the lower parts of the valleys. It may in fact be stated as a general rule that wherever we find an alluvial level by the side of a stream, we may be sure that the stream is not now deepening that part of its valley, but has reached the local base-line of erosion.

As nearly all rivers flow over rocks of different hardness and cut their way back by a series of rapids and waterfalls, it has been suggested that the position of falls and rapids is a guide to the age of the river,[1] its age being great in proportion as these are near to the sources of the river. With certain limitations and exceptions this is doubtless cerrect; but, as we have seen, an upheaval of the sea-board may cause a new set of rapids to be developed: while, therefore, the presence of rapids in the lower part of a river-course does not prove the valley to be of late origin, their limitation to the higher parts of the tributary streams is certainly an indication of the ancient establishment of the drainage system.

It should also be noticed in passing that the lowering of the water-level of a large lake will have the same effect on the streams running into it as the lifting of a whole country has on the streams running into the sea.

[1] "Quart. Journ. Geol. Soc.," vol. xxxv. p. 116.

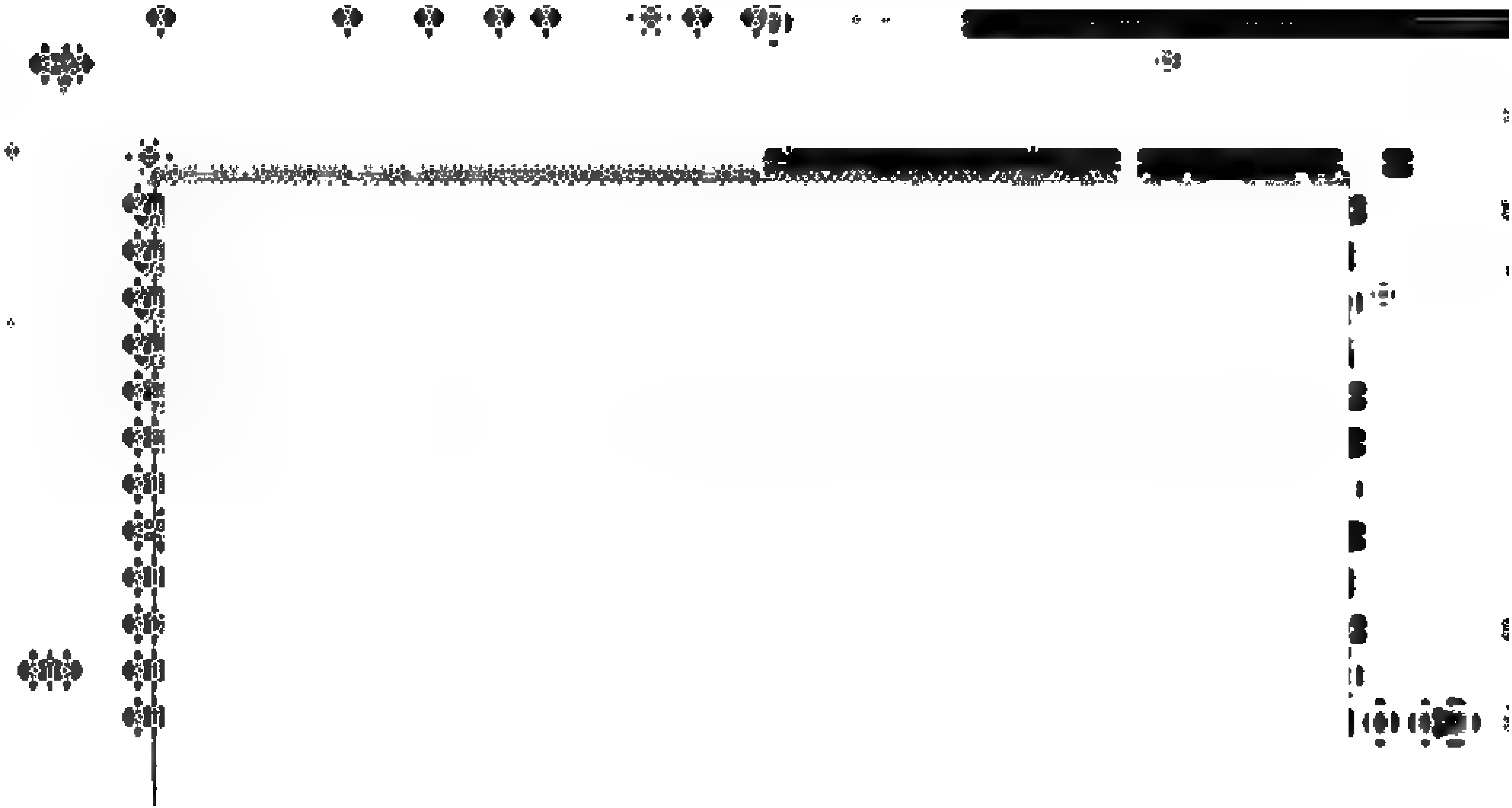

Fig. 198. An Alluvial Level in a Silted-up Valley.

From the above considerations it is evident that the influence which movements of subsidence or upheaval exercise upon the power of rivers to erode their channels is most important, and the author believes that it is mainly because the advocates of river-erosion have neglected to insist upon this point that many persons have been unable to see the cogency of their arguments, or to believe that rivers have had any share in the excavation of their valleys. It is said by these sceptics that the rivers are not now deepening the valleys in which they run, and, therefore, that the valleys cannot have been made by the rivers; some have answered this by supposing that the volume of water in the rivers was much greater formerly than it is now, but the real answer is that these streams have reached their base-lines of erosion, and consequently that observations on their present action will not enable us to realize how they have excavated the valleys in which they flow. This seems to be the case with many of the large European rivers, especially the Rhine and Moselle, whose valleys were described on p. 147.

The southern part of England is another region where the valleys are not now being deepened. At no remote period of geological time the whole of the British Islands stood at a much higher level than they do now, and during this time erosion was very active, and the whole valley system of the country was gradually elaborated. After this period came a succession of movements the details of which are not yet fully known, but it is fairly certain that the last movement was a tilt from north to south, causing a slight elevation of Scotland and a depression of southern England, which finally became severed from the continent. The result of this differential movement was to check the velocity of the English streams, and to cause the formation of those alluvial levels or water-meadows which are such a characteristic feature in the valleys of southern and central England. The north of England experienced little change of level, but in Scotland the rivers have cut channels through the old alluvia and estuarine deposits, and are probably still in many places deepening the upper parts of their valleys among the hills and mountains.

We have hitherto assumed that the only movement

capable of modifying erosive agencies was one which changed the level of the whole country in relation to that of the sea; but on a large continent local inland districts may be affected by earth-movements, and within a single system of drainage a tract of country may be raised or lowered without any alteration of level occurring on the sea-board. Lateral pressure or volcanic action may come into play after the establishment of a valley-system. It may cause the upward bulging of certain portions of the surface over which the streams are running, but if the upward movement is sufficiently gradual, and the main river has sufficient velocity, this river may cut its way down through the rising tract without altering its course, and so long as the main stream maintains its original channel, so long will all its tributaries continue in theirs. The result will be the formation of deep gorges or cañons, the great depth of which is due to the local upward movement of the ground; that is to say, the river has acted as a fixed saw moving along one plane, while the rocks through which it has cut its channel have been pushed upward from below.

This is believed to be the explanation of the great cañons of the Colorado and the Green rivers. It was stated on p. 148 that the Green river traverses the Uinta mountains; these mountains are formed by a single broad anticlinal fold, exposing a thickness of 24,000 feet of rock. In the northern cañons the beds dip to the north, and the river, following a serpentine course, eventually reaches the axis of the range, along which it runs in a wide and open valley for a distance of thirty miles; then it suddenly turns to the south and traverses the southern flank of the great fold in another series of cañons. The American geologists believe that the course of the river was established before the uplift, when the rocks were nearly horizontal, and that the elevation of the fold was so slow that it did not divert the river from its original course. Professor Powell's words are: "We may say, then, that the river did not cut its way down through the mountains from a height of many thousand feet above its present site, but having an elevation differing but little perhaps from what it now has, as the fold was lifted it cleared away the obstruction by

cutting a cañon, and the walls were thus elevated on either side. The river preserved its level, but the mountains were lifted up; as the saw revolves on a fixed pivot while the log through which it cuts is moved along."[1]

In the same way, although the beds seen in the cañons of the Colorado are generally horizontal, these cañons are not cut through one great unbroken plateau, but through a series of plateaux or great geographic tables and terraces separated by faults or monoclinal folds. The Kaibab plateau (see fig. 427) is one of these tabular elevations; and Professor Powell sums up his description of the structure of this region in the following words: "All the facts concerning the relation of the waterways of this region to the mountains, hills, cañons, and cliffs, lead to the inevitable conclusion that the system of drainage was determined antecedently to the faulting and folding and erosion, and antecedently also to the formation of the eruptive beds [lavas] and [volcanic] cones." (*Op. cit.*, p. 198.)

Dr. Emil Tietze[2] has also expressed the opinion that in many cases where mountain ranges are breached by transverse valleys the upper part of the river-valley is older than the mountain-range, and that, as the rocks of the range were slowly raised out of the water, the river prolonged its course over the land thus formed, cutting its channel deeper and deeper as the range became higher and higher. In this way he explains the transverse valleys which are cut across some of the highest ridges of the Elburz mountains in Persia; and he believes that the gorges of the Indus and Brahmapootra through the Himalayas have been formed in the same way. These rivers take their rise on the slopes of the Karakorum and Kuenlun ranges, both of which are far older than the Himalayas; the rivers which flowed off them would extend themselves southward when upheaval began, and cut valleys through the Himalayan rocks as the latter slowly rose into mountains.

Influence of Movement on Marine Erosion.—It has been stated that if the land remained at one level for

[1] "Exploration of the Colorado River, Washington, 1875," p. 153.

[2] "Jahrbuch der kais.-kön. geol. Reichsanstalt. Vienna," xxviii. p. 581. See "Geol. Record" for 1878, p. 197.

a sufficient length of time it would be gradually worn away, leaving only a submarine flat or plain, covered by a shallow sea. Some of our present plains and table-lands have been produced in this way, the mountains that once stood over them having been removed by the erosion of the sea. The destruction of Graham's Island in the Mediterranean, and the shallow flat left in its place, illustrate this result.

We have seen, however (Part I., Chapter V.), that the land is anything but stationary, and that every part of it is liable to be moved upwards or downwards through the upper surface of the sea. During such movements, the waves will, of course; act upon every contour line that is successively brought within their influence. Mr. Jukes has compared the external action of the sea to that of a fixed engine with a horizontal planing and graving machinery, contrived to carve into any substance, while the earth-movements are forces acting vertically, raising or lowering the substance through the horizontal cutting plane.

If the land is elevated, the old coast with its line of cliffs is carried inland to a certain distance, and the new raised tract forms a terrace or platform in front of it: if the vertical uplift has not been very great this tract will only be a narrow terrace like those described in Part I., Chapter V., but if after remaining stationary for a long period of time the region be rapidly raised through 200 or 300 feet a broad platform will be exposed. An elevated platform of this kind is found along the north coast of Spain, and is thus described by Dr. C. Barrois: "The rocks of the whole Cantabrian coast, from Galicia to Santander, form rugged mountains, which rise like cliffs at a distance of 3 or 4 kilometres (2 to 2½ miles) from the coast-line, while the space between the sea and these mountains is a narrow plain; the beds being levelled as if a coast road had been purposely constructed along the base of the mountains." "The altitude of this plain or platform appears to be about 200 feet above the sea, but the tracts formed of sandstone are more elevated than those of limestone, and the latter are higher than the tracts of schist. The numerous torrents which descend from the mountains cut directly across the plain, and give rise to the formation of a great number of transverse sections. . . . The com-

parison of this plain with the shore platform now in process of formation shows the resemblance between them: the denuded surface, which forms a broad terrace along the Cantabrian shore, is nothing but an elevated marine platform, a typical example of the plains of marine denudation described by Professor Ramsay."[1]

On the other hand, if a region after standing at one level for a certain length of time be depressed to a lower level, the height of its cliffs is diminished, and the waves have a smaller mass of rock in front of them; consequently they eat much more rapidly into the land, cutting it back at a higher level than before, and carrying out a fresh plain of erosion.

It will be instructive to consider a special case of depression, where the land, after having stood at a certain level for a long period has been permanently lowered, and

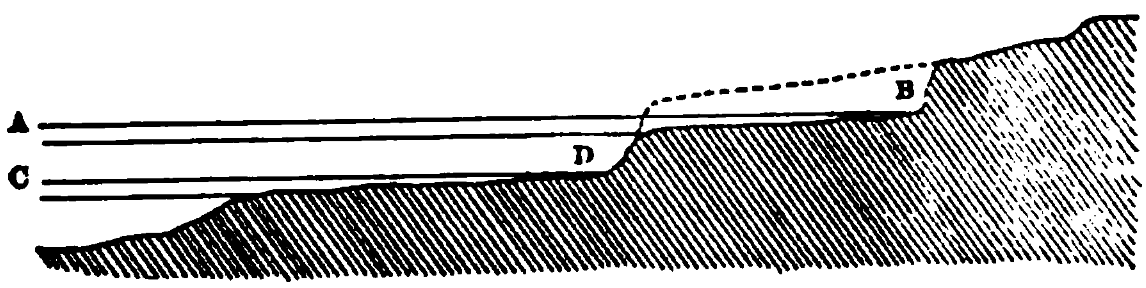

Fig. 199. The effect of Depression on Marine Erosion. The double lines indicate high- and low-tide levels.

then allowed to remain stationary again for a considerable time. It is evident that, during the second period of rest, the waves will carve out a second platform, at a higher level than the old one formed during the first period.

Fig. 199 is intended to illustrate the result of this process. The line C D indicates the level of high tide during the first period, when the lower platform was formed. Depression of the land then caused the sea to flow over this platform, till its high-tide level corresponded with the line A B. The waves continued to cut down the cliffs which once stood over D; but the line of non-erosion being now at a higher level, they could not wear down the new platform to the plane of the older one, which, therefore, remains

[1] "Récherches sur les Terrains Anciens des Asturies et de la Galice," "Mem. Soc. Géol. du Nord," tom. ii. p. 619.

as a submarine terrace, until it is covered and concealed by newly-formed deposits.

The Isle of Wight may be cited as an instance of an island standing upon a platform of this kind, produced by the combined effect of subsidence and marine erosion. The island lies entirely inside the line of 10 fathom-soundings, so that an elevation of only 60 feet would unite it to the coast of Hampshire, leaving a level platform, with raised beaches all round the present shore of the island. We may, therefore, assume that its cliffs once stood at the outer edge of this platform, and were continuous with those of Hampshire and Sussex, and that they have been gradually cut back to their present position by the erosive action of the sea.

There is good reason, moreover, for believing that this amount of erosion does not represent the total loss of land which has taken place on the south side of the island in comparatively recent times. There are, at any rate, certain peculiarities in the courses of the rivers, which suggest that when the present system of drainage was established, large areas of land existed over the sites of Brixton and Sandown Bays. Mr. Codrington has pointed out that the short streams which flow into these bays must once have had much longer courses, and were probably tributaries of two large rivers which ran northward into the Solent (see map). He thus accounts for the remarkable fact that both the Yar at Freshwater and the Sandown branch of the Brading river rise close behind the present beach, below high-water mark, and flow northward through the chalk hills. Consequently, he supposes that the present short streams are merely the abbreviated remnants of much larger rivers, the drainage basins of which have been entirely destroyed by the continual encroachments of the sea.[1]

An instance on a larger scale is furnished by the great submarine platform on which the British Islands themselves stand. It is a well-known fact that the seas surrounding our islands are comparatively shallow, and nearly everywhere less than 100 fathoms deep. The 100 fathom line, in fact, starts from the Bay of Biscay, and passes out-

[1] "Quart. Journ. Geol. Soc.," vol. xxvi. p. 528.

side Ireland, at a distance of about 50 miles from its western coast, thence it trends north-eastward, outside the Hebrides and the Shetland Islands.

Outside these limits the sea-bottom plunges rapidly down to the 500 and 1,000 fathom lines, and it is therefore supposed that the European continent at one time extended westward as far as the boundary of this submarine platform, and that this platform was formed during periods of subsidence, when the sea ate its way farther and farther across the land, planing down its prominences and filling up its hollows until the movement ceased and the present configuration of land and water was produced. If now upheaved the platform would form an undulating plateau, like a Siberian steppe, only diversified by occasional lakes on the sites of the deeper holes which exist on the sea-bottom.

Marine Erosion compared with Subaerial Detrition.—In any comparison between the relative amount of erosion performed by the sea, and that accomplished by the other detritive agencies at work upon the surface of the land, the above considerations must be borne in mind.

At the present time, where the land is stationary or rising, the sea can only act on the edge of the land, so that the extent of marine erosion must be comparatively small as compared with that effected by the subaërial agencies which act upon every foot of its surface. Dr. Geikie has calculated that if the sea eats away the edge of a continent at the rate of 10 feet in a century, and subaërial agents remove a layer one foot thick from its general surface in 6,000 years, the whole continent of Europe would be entirely worn away by the latter agencies before the sea could pare off more than a mere marginal strip of land 150 miles in breadth.

But, as he truly says,[1] "In estimating the amount of influence to be attributed to each of the denuding agents in past times, we require to take into account the complicated effects which would arise from the upheaval or depression of the earth's crust. If frequent risings of the land or

[1] Geikie, "Text Book of Geology," third edition, p. 448.

elevations of the sea-floor into land had not taken place in the geological past, no great thickness of stratified rocks could have been formed, for the first continents must soon have been washed away." It also follows that the areas upheaved must have been more considerable than the areas depressed, and therefore, even in past times, the amount of detrition effected by rain, frost, springs and rivers, must have always been greater than that accomplished by the sea.

CHAPTER III.

THE ORIGIN OF SOME SPECIAL PHYSICAL FEATURES.

IN the first chapter we discussed some of the conditions which have guided the erosive agencies in selecting certain lines of action, and in developing certain general features of the earth's surface; we now propose to pursue the subject and to explain the origin of some of the special features and local peculiarities which meet the eye of the observer among mountains, highlands, and table-lands.

Mountain peaks may be defined as the sharpest forms of watersheds, produced by the continuous scarping of hard rocks at altitudes where the atmospheric agencies work with the greatest power. Their peculiar shapes depend chiefly on the kind of material out of which they are carved. Almost every kind of rock produces its own special kind of mountain scenery, and the outlines presented by peaks of granite, quartzite, schist, slate, sandstone and limestone differ so greatly from one another that an experienced geologist can often make a good guess at the kind of rock which forms a mountain peak long before he reaches it.

Granite hills are always broad, round-shouldered heights, only here and there forming anything which can be called a peak, these consisting of loose weathered blocks, piled one on another, and often resembling masses of ruined masonry. Hills of gneiss are similar, but often have steeper slopes.

Quartzite hills always form sharp triangular ridges or conical peaks, which often have some resemblance to volcanoes, but generally have steeper and straighter outlines. Schiehallien, in Perthshire, is a notable instance of a

quartzite hill; seen from the south-east it appears as a rocky ridge with a long gentle slope on the eastern side, and a steep descent toward the west, but viewed from the north-west it appears as a perfect cone, "raising its gleaming peak of snowy quartzite to a height of 3,547 feet."[1] But "nowhere in the Highlands," says Sir Arch. Geikie,[2] "can the whole of the distinctive features of quartzite scenery be seen on so grand a scale as among the mountains of Islay and Jura. In the latter island the quartz-rock rises into the group of lofty cones known as the Paps of Jura, 2,571 feet above the sea, which almost washes their base. The prevailing colour is grey, save here and there where a mass glistens white as if it were snow; and as the vegetation is exceedingly scanty, the character of the rock and its influence on the landscape can be seen to every advantage."

Hard sandstones and grits, when nearly horizontal, have also a tendency to form huge single pyramidal mountains like Morven and Maida Pap in Caithness, and the wonderful groups of isolated sandstone mountains which are such conspicuous objects in the west of Sutherland and Ross. To quote again from Sir Arch. Geikie's admirable descriptions of Scottish scenery, "these huge pyramids, rising to heights of between 2,000 and 4,000 feet, consist of dark red strata so little inclined that their edges can be traced by the eye in long level bars on the steeper hillsides and precipices, like lines of masonry. . . . These huge isolated cones are among the most striking memorials of denudation to be seen in the British Islands. Quenaig, Canisp, Suilven, Coulmore, and the hills of Coygach, Dundonald, Loch Maree and Torridon are merely detached patches of a formation, not less than 7,000 or 8,000 feet thick, which once spread over the north-west of Scotland" (*op. cit.*, p. 203).

When the sandstone strata have a decided dip or inclination the conical form of peak is more or less modified, such hills generally breaking into a steep precipitous slope on the outcrop side, and often forming what is termed

[1] "The Scenery of Scotland," second edition, p. 205.
[2] *Op. cit.*, p. 207.

a *mural escarpment* that is so steep as to resemble a wall, while the opposite side of the ridge falls away in a longer slope, which tends to become a *dip-slope,* that is, the surface of the ground often coincides with the surface of a particular bed for some distance.

Hard and massive limestones generally develop tall columnar or turret-like peaks, the forms depending partly on the horizontality or inclination of the beds, but more especially on the lines of jointing. Sometimes the general trend of a limestone mountain is determined by the direction of one set of joints, while its separation into blocks and peaks is determined by another set having a transverse direction. This is well illustrated in the case of the Drei Zinnen, an excellent view of which forms the frontispiece to this volume.[1] These are peaks of hard Dolomite, and form part of the region of the Dolomite Mountains in the Tyrol. The view from this very spot has been thus briefly described:—"From Landro, Monte Cristallo, shooting up in towers between its glaciers, is the dominating object. Not far from the post-house, however, through a gorge opening eastward there is an apparition of three splintered spires (the Drei Zinnen, or three battlements) than which in the way of mountains I know nothing stranger."[2]

The hard crystalline schists form mountain crests which often present a sharp and serrated array of peaks. Such serrated ridges occur among the gnarled schists which tower into the mountain heights of Inverness; and the rough, rugged, and craggy outline which their summits exhibit may be ascribed partly to the influence of foliation and jointing, and partly to the unequal weathering due to the differences of hardness and texture in the rock material.

Fig. 200 is a view in the Graian Alps, borrowed from Professor Bonney's "Alpine Regions," and shows a peak composed of chloritic and micaceous schists which belong to the upper part of the crystalline series of the Alps. Many of the eminences, which are termed *aiguilles* in Swit-

[1] This plate is borrowed from Professor Bonney's "Alpine Regions," and was drawn by Mr. Whymper from a sketch by Professor Bonney.

[2] "The Dolomite Mountains," by Messrs. Gilbert and Churchill.

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stone cliffs, B, which form the lip of the cup-shaped hollow. "The most remarkable thing about the cliffs," says Professor Bonney, "was the belt of reddish shaly rock which was furrowed by a vast number of little gorges which were often only a few yards apart, and occasionally united, so that this part of the cliff really looked like a badly-ploughed field set up on end. Down these gorges, many of them dry in August, little rills descend from the snows on the ledges, and in the combes above, and these have generally made some trace corresponding with their size on the harder limestone below, sometimes a mere stain, sometimes a well-marked groove."

The Creux des Champs on the northern face of the Diablerets, the Fer-à-cheval, near Sixt in Savoy, and the Creux des Vents in the Jura, are all good instances of large cirques, and are described by Professor Bonney in the paper above quoted.

The existence of similar cirques and corries in the mountains which lie between the Red Sea and the valley of the Nile,[1] and where there are no traces of glacial action, is an additional proof that they cannot be attributed to the action of glaciers.

Cols and Passes.—A col or mountain pass is a depression in the ridge of a watershed connecting two lateral valleys with one another. Every gradation may be found, between a mere notch in the crest of a ridge, and a profound gap or pass connecting two long and deep valleys. The notch is formed by the recession of the heads of the two valleys till the crest or ridge between them is worn in to a col or gap, and, finally, if the action is continued long enough, into a deep pass which can be used as a roadway.

The formation of such passes in the Highlands of Scotland is well described by Sir A. Geikie in the following words:[2] "Among the high grounds where disintegration proceeds apace, the gradual narrowing of ridges into sharp narrow knife-edged crests, and the lowering of these into cols or passes, can be admirably studied. Where two

[1] See "Geol. Mag.," Dec. 2, vol. iv. p. 477; confirmed by J. Walther, "On the Denudation of Deserts," see "Nature," 1891, p. 556.

[2] "The Scenery of Scotland," p. 179.

glens begin opposite to each other on the same ridge, their corries are gradually cut back until only a sharp crest separates them. This crest, attacked on each front and along the summit, is lowered with comparative rapidity, until, in the end, merely a low col, pass, or balloch may separate the heads of the two glens."

When the ridge between the two glens has been so far reduced that there are steep slopes up from it to the higher part of the watershed on each side, water will course down these slopes after heavy rains, and, spreading more or less over the col, will help to lower it still further, and to transport its débris into one or other of the two glens. In this way the pass may eventually be so greatly lowered that the two valleys are converted into one long continuous valley, the original site of the dividing ridge or watershed being scarcely perceptible, and only to be detected by the fact that there is a point where the water flows in opposite directions.

Such continuous valleys are not uncommon in Scotland and other mountainous regions, and some of them traverse portions of the Highlands from sea to sea. Thus the valley of Loch Carron is continued across Ross-shire to Contin and Cromarty Firth, its watershed being only 600 feet above the sea, and only perceptible by the flow of the water in the valley. A smaller but equally remarkable valley is that which runs southward from Loch Fyne through Cowal to Holy Loch, and contains the narrow waters of Loch Ech. It is quite possible, however, that in these and other cases the existing watershed does not exactly coincide with the original line of division between two glens; considering the great age of the Scotch valleys, and the numerous earth movements which they have experienced, its present position may have been determined by subsequent uplift, or by mounds of glacial débris carried down some lateral glen and heaped across the longer valley.

Mesas and Buttes.—These are both American terms, though the first is of Spanish and the second of French origin; they are constantly used by American geologists to denote certain forms of hills which are frequent in that country.

Mesas are the long flat-topped tracts of high ground which remain where a system of large valleys has been carved out of a plateau of hard rock; and they are most characteristically developed where the strata are nearly horizontal. Great sheets of basaltic lava, such as those of New Mexico, and of Auvergne in France, give rise to the formation of mesas.

A *Butte* is an isolated steep-sided hill of small superficial area, and is, strictly speaking, an outlying block or mass which has been detached from a plateau by the erosion and removal of the intervening parts.

The edge of a plateau of horizontal or slightly inclined rocks is generally carved by the action of rain and wind into a series of bays and promontories, and the ends of the latter are eventually separated so as to stand out on the lower plain like sea-stacks off the headlands of a coast-line. If the uppermost layer of the plateau is harder than those below, the butte will for a time have a flat top, but if the beds are of nearly equal hardness the butte will have a more or less conical form.

Fig. 202 is a view in the upper valley of the Green River, Wyoming, U.S., showing a portion of a gently inclined plateau which has been eroded into a series of detached blocks and buttes. Such forms are frequent in the "Bad-lands" of the Western States. The group of flat-topped mountains in British Guiana, of which Roraima is the most conspicuous, are remnants of an ancient plateau, and may come under the denomination of buttes. Similar forms occur in other parts of the world, and the term may therefore be usefully introduced into geological and geographical nomenclature.

Gravel Ridges.—In some districts the natural drainage of the country has altered so greatly in the course of ages, that long banks and ridges of river gravel are found in situations where no rivers could now flow. Long series of such gravels occur in the neighbourhood of Cambridge.

They commence in a series of patches which occur at intervals along the sides of the long, but now dry, valleys which run through the chalk hills. The farther they are traced down each valley the larger do the patches become, and the greater is the difference of level between the bottom

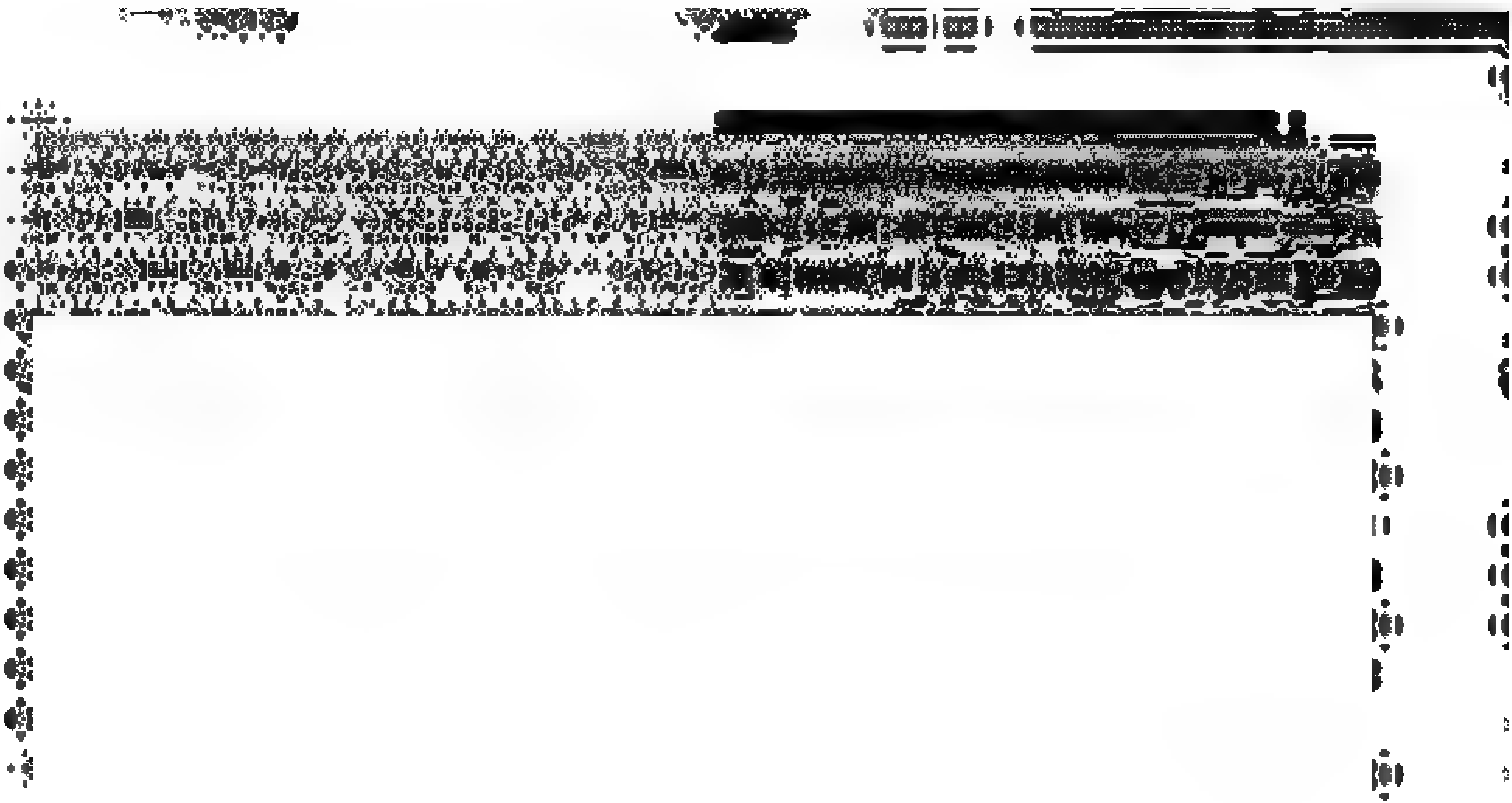


Fig. 202. View on the Green River.

of the present valley and the height at which the patches of gravel occur, till, at last, they diverge altogether from the existing line of drainage, and stream out to form long-continued gravel-capped ridges which trend more or less in the direction of Cambridge.[1]

Fig. 203 is a section across one of these ridges, near Wilbraham; it owes its existence as a ridge to the river-gravel which rests upon it, and has protected the under-lying

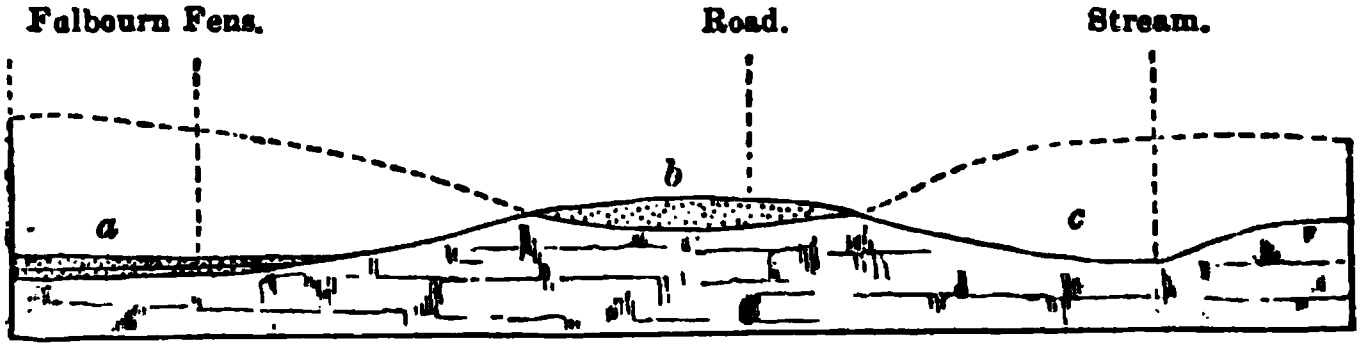


Fig. 203. Gravel Ridge near Wilbraham, Cambridge.
a, Modern gravel. *b*, Ancient gravel. *c*, Chalk.
Horizontal scale, 2 inches to a mile.

chalk from destruction; the bottom, therefore, of the ancient valley is here preserved, while the hills and slopes which once formed its sides have long since been destroyed and washed away by the wasting action of rain and springs. The dotted lines in the figure indicate the general outline of the ground at the time when the gravels were formed.

[1] See "Post-Tertiary Deposits of Cambridgeshire," p. 46, and "The Geology of Cambridge," Mem. Geol. Survey, p. 82.

CHAPTER IV.

PROOFS OF THE AMOUNT OF MATERIAL REMOVED FROM EXISTING SURFACES.

IN this chapter we shall consider some geological features which furnish absolute proof of the enormous amount of detrition and denudation that has taken place in some parts of the country; these considerations will enable us to realize what vast thicknesses of rock have in many cases been removed during the process of erosion, which has led to the development of the present physical features of the country. They may be treated conveniently under the following heads:—1, evidence from the outcrop of strata; 2, from faults; 3, from outliers and inliers; 4, from mountains of upheaval.

1. *Outcrop of Beds.*—Where a series of beds dip one beneath another, as in fig. 192, over a considerable breadth of ground, it is clear that they cannot have originally terminated in that manner, for it is the very fact of their abrupt truncation that causes them to crop out on the present surface. The higher beds must originally have extended for long distances beyond their present lines of outcrop, and a very great thickness of rock must once have existed above the present surface.

Where a surface has been formed across anticlinal and synclinal folds, the outcrops of the different beds supply a means of actually estimating the minimum thickness of rock which has been removed since the folds were formed. Thus, in fig. 204, the distance between C and D may be several miles, and the thickness of the beds, 2, 3, 4, 5, may be respectively 100, 150, 50, and 300 feet. It is clear that all these beds must originally have been continued over

the anticlinal, A, or they could not have been brought into the synclinal trough, S. The minimum thickness of rock, therefore, which has been removed from the surface over the point, A, must be 600 feet; and if any more beds came in with the same dip beyond D, their thickness would have to be added to this amount.

Fig. 174, p. 519, illustrates an actual case in which this estimate may be made; if the thickness of the slates between B and D be 5,000 feet, it is clear that a depth of rock of more than that thickness must have been removed from the top of the anticlinal fold, B, and, further, the same thickness of rock must once have extended across the Menai Straits, and all over Anglesea, unless the strata thinned in that direction. That much of it really did so extend is

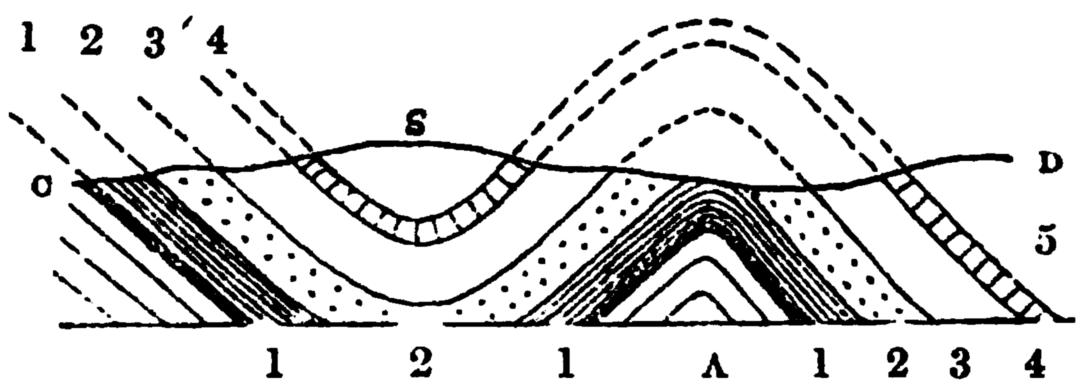
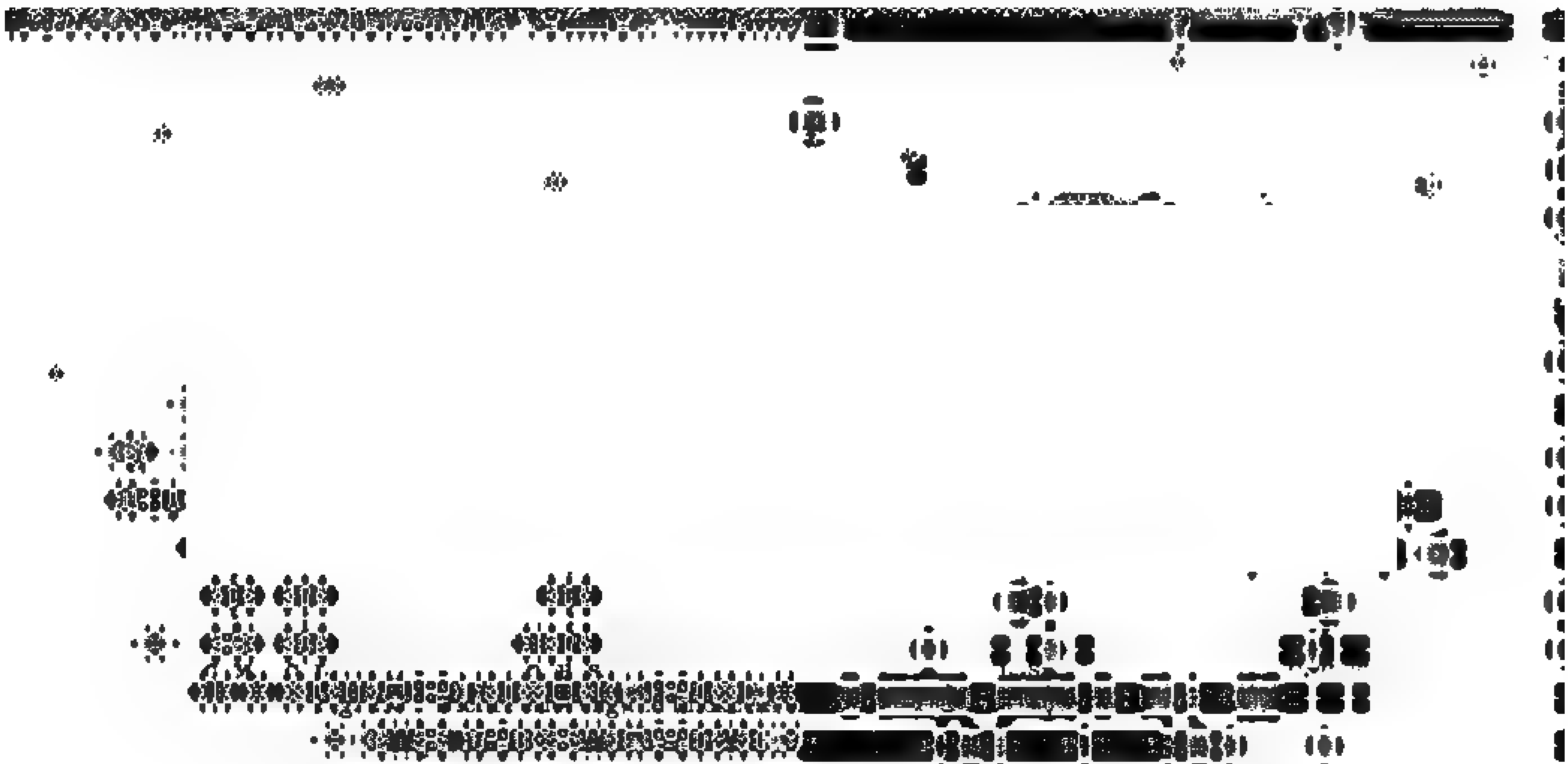


Fig. 204. Thickness of Rock removed by Denudation.

proved by some of the beds being brought in here and there by faults and synclinal curves.

In the same way Sir A. Ramsay has shown that in some parts of South Wales a thickness of about 11,000 feet of rock has been removed from the present surface of the country.[1] Fig. 205 is a reproduction of one of his sections slightly altered for the purpose of making it clearer to the student. The strong irregular line which limits the ornamented part of the section represents the actual surface of the ground along which the section was taken, and the horizontal line a little below it represents the level of the sea. The central group of rocks, L. S., contains a bed of limestone which is easily recognized, and the destroyed portions of it which originally connected the present outcrops are indicated by dotted lines. The beds which overlie the

[1] "On the Denudation of South Wales," Mem. Geol. Survey, vol. i. p. 297.



Scale, horizontal and vertical, one inch to one mile. S S, Sea-level. G G, Surface of the ground.

limestone on each side of the arch are about 1,500 feet thick, and their upper limit is also indicated by dotted lines. The sandstones which succeed must also have been folded over the arch, and are in the figure represented as coming in again on the north. They are from 4,000 to 5,000 feet thick in this district. How much of C. L. and C. M. (the Carboniferous limestone and Coal-measures) also extended northward and lay over the central area when the arch was first formed we do not know, but some of these beds did. The area shaded by parallel oblique lines is therefore the least amount of rock that has been removed from above the present surface of the ground. As the scale of the diagram is one inch to a mile both horizontally and vertically, the amount is easily measured, and found to be nearly 7,000 feet. A little further west, over the Vale of Towey, the amount removed is found to be about 11,000 feet.

In the same manner Sir A. Ramsay demonstrated that a thickness of from 8,000 to 10,000 feet of Carboniferous rocks had been removed from the central parts of the Mendip Hills in Somerset before the formation of the newer rocks which now surround them. A similar thickness of the same beds has been removed from the downs west of Bristol, as shown in fig. 189; and not only so, but a further thickness of about 3,500 feet of newer strata, Trias, Lias, Oolites, Greensand, and Chalk, has been removed during the production of the present surface of the country.

The south of Ireland also furnishes many good instances of great denudation; its geological structure has already been partially described (see p. 552, and figs. 187, 190). It was stated that the coal-measures, which now only occur as isolated patches, had originally a very wide extension over this part of the country, overspreading and overlapping the Carboniferous limestone, as shown in fig. 190. So great, however, has been the loss of material during the process of detrition and denudation by which the present physical features have been produced, that not only have the coal-measures been removed from the greater part of the country, but the erosion has in many places extended through the whole thickness of the Carboniferous

limestone, and has cut deeply into the Old Red Sandstone below.

In some places the erosion has extended even to the bottom of this division, so as to re-expose and trench into the Ordovician rocks upon which the sandstones were deposited. From the extent of this denudation, therefore, it can be proved that a thickness of between 5,000 and 6,000 feet of rock has been removed from some parts of the district.

2. *Evidence of Faults.*—Equally convincing is the evidence furnished by the great dislocations which traverse every country. Some of these are vertical displacements to the amount of several thousand feet (see p. 450), and yet they seldom produce any effect on the surface of the ground. To take an extreme case as an illustration, there is a fault traversing the Appalachian Mountains in North America, which has a vertical throw of 20,000 feet, and yet the surface is so planed down that a man can stride across the line of fault, with one foot on a bed which was originally[1] 20,000 feet above that on which the other foot rests. Another American fault, described by Powell as running along the north side of the Uinta Mountains in Wyoming, has a displacement of nearly 20,000 feet, and the same author estimates the amount of rock which has been removed from the central axis of the Uinta fold to be not less than 24,000 feet. Again, many of the maps of the "Geological Survey of Great Britain," especially those of the coal-fields, show so many faults that they are covered with a network of white lines. These faults are of various magnitudes, from a few feet to many hundred, and yet no sign of such displacements is visible at the surface, which may be a continuous tract of undulating fields and meadows. In all these cases it is clear that a thickness of rock equal to the maximum amount of vertical displacement has been removed from the surface of the country.

3. *Outliers and Inliers.*—An outlier is, as the name implies, an outlying or isolated portion of a bed, which has been separated from the main mass with which it was

[1] Campbell, "Frost and Fire," vol. ii. chap. li. p. 333.

originally connected by erosion and denudation, just as an island is separated from the mainland (see fig. 187, p. 552, where outliers of Old Red Sandstone are shown).

The simplest form of an outlier is that which so often occurs in connection with a line of escarpment, the unequal recession of which has left a series of bays, promontories, and outliers. It is easy to see how the neck of a promontory may be gradually worn through by the action of rain and springs until it is converted into an isolated hill, the very existence of such a hill becoming a proof of the former extension of the beds, and of the recession of the escarpment.

Very frequently the existence of the promontory and subsequent outlier is due to a slight synclinal curvature of the beds, the inward dip giving them a greater power of resistance to detritive agencies, and diminishing the liability to landslips. So often is this the case that the very occurrence of an outlier affords strong presumptive evidence of this inward dip, although the actual inclination of the beds may be so slight as to be inappreciable in a quarry.

Conversely, an anticlinal curvature, when denuded, often gives rise to what is called an inlier, which may be defined as the isolated exposure of an underlying bed amidst others which are geologically above it.

Figs. 206 and 207 are respectively a plan and section illustrating the occurrence of an outlier and an inlier. A A is an escarpment formed by successive beds of ironstone, sandstone, and chalk; O is an outlier of the chalk and sandstone, resting on a promontory of the ironstone, which is still connected with the main mass by a narrow neck. I is an inlier of the sandstone and ironstone, brought up by an anticlinal curve, and exposed in a valley excavated out of the long slope of the limestone. The section is taken along the line, S S, and illustrates the relations of the external features to the internal structure of the ground.

In the case represented by fig. 206, which has been suggested by the structure of the Chalk Wolds of Lincolnshire, the outlier and inlier are caused by undulations parallel to the strike, but they are perhaps more often produced in nature by undulations across the strike, of the kind illus-

trated by fig. 111; the synclinals leading to the formation of outliers beyond the escarpment, and inliers occurring where the anticlinal folds happen to be crossed by some river-valley inside the main line of escarpment.

Among the older rocks which have been thrown into much sharper curves and contortions, outlying basins sometimes occur containing a great thickness of beds in their centre (see fig. 194), showing that a corresponding thick-

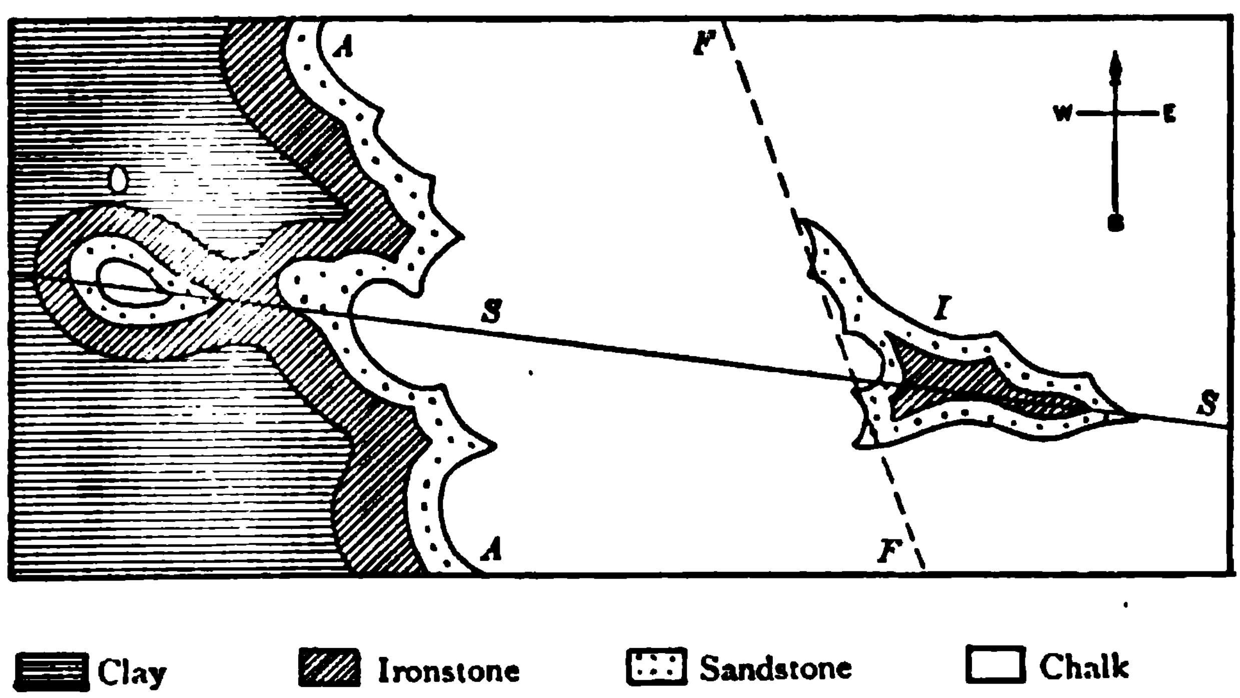


Fig. 206. Plan of Outlier and Inlier.

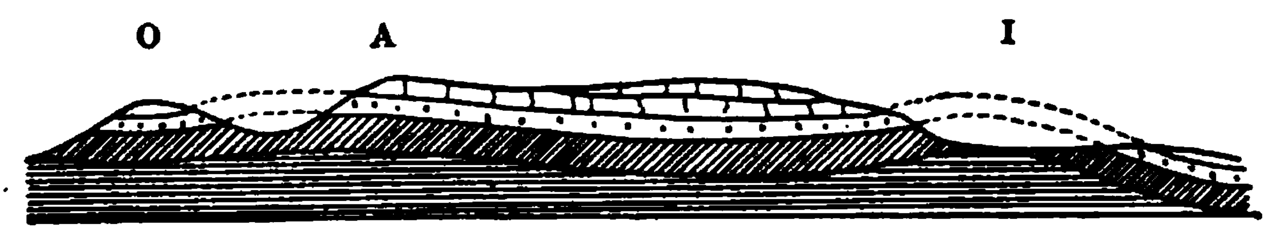


Fig. 207. Section along line S S.

ness must have been removed from the surrounding districts.

Flexures, however, are not the only conditions which give rise to the production of outliers and inliers. Faults, by causing an upthrow or downthrow of beds, may bring them into such positions that portions are afterwards isolated by erosion. Thus, if the beds in figs. 206 and 207 were traversed by a strike-fault along the line marked F F, instead of being bent into an anticlinal, an inlier might still be produced by erosion, though, in that case, its

[illegible] line of fault.
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of limestone, the beds of which are bent into an anticlinal curve, which becomes almost a periclinal at the north end of the hill. The surrounding escarpments are formed by the outcrop of several beds of hard grit and sandstone interstratified with softer shales, while it is along the course of the latter that the valleys of the district have been excavated. The dependence of physical features upon geological structure is here, therefore, excellently illustrated.

From the map (fig. 209) it is seen that the country is traversed by two main lines of fault, which, together with a cross fault on the north-west, completely cut off the Crich Hill area from the surrounding district. The triangular tract bounded by these faults has been pushed bodily upwards, or else the tracts on each side have been let down, till the upper surface of the limestone (1) was

R. Derwent.

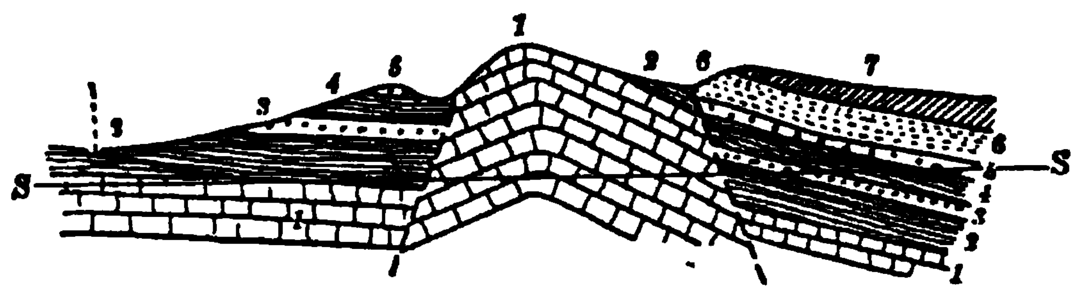

Fig. 210. Section through Crich Hill.
Along the line A B in fig. 209.

raised above the level of the sandstone (6), as shown in the section (fig. 210) along the line A B. Furthermore, during the process of erosion and denudation by which the physical features of the country have been produced, the whole of the beds, 2, 3, 4, 5, 6, 7, have been removed from the surface of the limestone that forms Crich Hill, so that this satisfies the definition of an inlier, and becomes a measure of the amount of the denudation that has taken place.

The thickness of beds 2 to 7 is here about 700 feet, but as they dip eastward they are covered by coal-measures to a depth of nearly 3,000 feet, and all these must originally have been continuous over the top of Crich Hill, and across the great anticlinal axis of the Pennine Hills into Cheshire and North Staffordshire. In the latter counties the beds above the limestone are very much thicker, so that the

thickness of rock removed from the western slope of the Derbyshire Hills must have been in some places more than 8,000 feet.

4. *Mountain Chains.*—A mountain chain differs from a range of hills, not only in its greater height and breadth, but in its geological structure. We have seen that a range of hills can be carved out of a set of gently inclined strata, for many escarpments form ranges of hills, such as the Cotteswolds and the Chiltern Hills; or out of undulated strata, as in fig. 194; or out of a single broad anticlinal fold, like that of Derbyshire or the Mendip Hills; or, finally, out of any mass of rock that is harder than the surrounding strata. A mountain chain, on the other hand, always consists of a number of parallel folds, and has been so ridged up that the oldest rocks are always found along

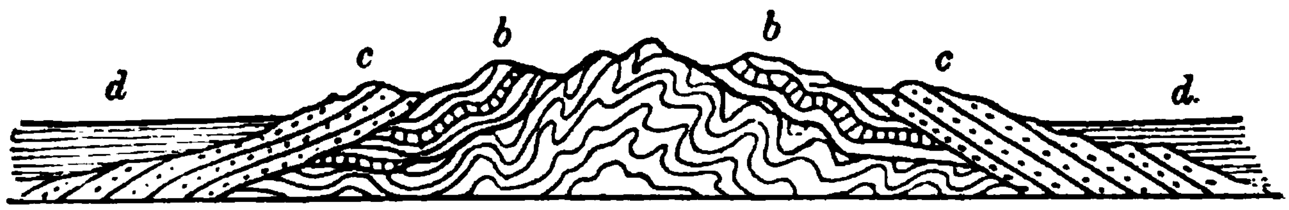

Fig. 211. Diagram showing three Periods of Upheaval.

the central axis of the chain. The appearances are those of great lateral compression, for—

1. The principal flexures are parallel to the length of the chain.

2. The plication and contortion of the strata is always greatest near and along the central axis.

3. The rocks composing the central axis generally show signs of pressure-metamorphism.

Again, mountain ranges have generally been formed by several successive uplifts at different periods of geological time. Thus fig. 211 may be taken as a diagram section through a mountain chain, *a*, *b*, *c*, *d*, being so many distinct formations, each unconformable to the other, and belonging to different geological periods. It will be seen that *a* had been flexured and raised into dry land before the formation of *b*, but was not then a mountain range; a second period of upheaval, initiating the range, occurred after the formation of *b*; and a third, completing the uplift, took place in the interval between the periods of *c* and *d*.

It can often be proved that the total amount of rock removed from the central axis of a mountain range is enormous. Captain Dutton has recently estimated the amount of rock removed from the Rocky Mountains of the Colorado region since their first upheaval, and believes it to have averaged 10,000 feet in thickness over an area of 13,000 to 15,000 square miles in extent. The Alps date from a still more recent period than the Rocky Mountains; but the compression to which the rocks composing them have been subjected seems to have been much greater, and therefore the total amount of vertical upheaval along their axis has probably been greater than in the case of the American range; but as the average height of the Alps is not much greater, the amount of denudation must have been greater in their case. This inference is borne out by the facts, for the thickness of the sedimentary deposits affected by the upheaval of the Alps, and exposed by denudation, has been estimated at about 50,000 feet; and this thickness may be regarded as the amount of rock removed from the summits of the Alps since their first upheaval.

It is necessary to guard the student against supposing that the removal of 50,000 feet of rock from a mountain range means that the range must have been 50,000 feet high at some period of its history. It need never have been much higher than it now is, because the two processes of upheaval and degradation have gone on together, and it was only in consequence of the repeated upheavals that so great a thickness of rock was removed. The process may be compared to the uprising of an iceberg out of the water, in proportion as the top is melted away by the sun, or to a piece of machinery, one part of which raises a block of wood or metal, while another part planes off the surface of the material as fast as it is brought within its reach.

Mountain ranges, therefore, differ from other hills as being mountains notwithstanding and in spite of the immense amount of detrition and denudation which has taken place over and around them.

General Conclusions.—From what has been said in this and preceding chapters the reader will be prepared to accept the statement that almost all the external

features of the land, hills, glens, valleys, and plains have been produced by erosion. Their form is a sculptured form, carved out of the rocks by the operation of all those agencies which have been described in the earlier chapters of this work. These agents combine to form a great surface-carving machinery, and the disturbing forces which result in the upheaval of land are chiefly efficient in bringing the rock within the influence of the erosive agents, and are seldom productive of any direct effect upon the form of the ground.

The only exceptions to the rule that the form of the ground is due to detrition and erosion, are to be found in the alluvial flats and deltas of rivers, in hills of blown sand, in areas covered by glacial moraines, and in the cones of active volcanoes on which the rain has not yet produced any appreciable effect.

It must be remembered, however, that in the case of mountain chains, though the forms of the peaks and valleys are the work of erosive agencies, yet the existence of the range itself is due to the force which has caused its elevation. Fig. 211 has been given as a simplified section across such a range, and though, of course, their structure is in reality much more complicated, still the diagram will serve to explain the process of their formation and to show what is meant by *hills of upheaval* compared with *hills of circum-detrition*, which have been amply illustrated by the preceding figs. 191, 192, 194. Detrition may have been equally active in both cases, and indeed the amount of material removed may have been greater in the former than in the latter case; but the comparative elevation of the ground is in the latter chiefly caused by the removal of the surrounding parts, while in the former the hills would have been more lofty if the detritive agents had been less active.

To sum up, therefore, the principal features of the earth's surface may be thus classified according to their mode of origin.

Valleys are of one kind only; they have all been formed by the erosive action of rain, springs, and rivers.

Plains are of two kinds: 1, plains of construction; 2, plains of erosion.

Plains of construction are such as are formed by the undisturbed extension of beds which retain the original horizontality of deposition. River deltas and alluvial flats, fens, marshes, and silted-up lakes, are instances of such plains. In this class may also be included the slightly inclined or undulating surfaces sometimes produced by the elevation of a shallow sea-bottom which special local causes have exempted from the action of marine erosion; such are the Pampas of South America, the Tundras of Siberia, and large tracts of Russia and Poland.

Plains of erosion are those which have been formed by marine erosion across the edges and outcrops of strata without reference to their inclination, flexures, or fractures. They are surfaces of planation formed by the march of the sea across the country. The limestone plains of central Ireland may be cited as an instance, and the country bordering the rivers Rhine and Moselle is another.

Hills are of three kinds: 1, hills of accumulation; 2, hills of circum-detrition; 3, hills of upheaval.

Hills of accumulation are such as have been formed by the piling-up of materials upon the surface of the ground. Volcanoes are the most important instances. (See plate at the end of the volume.) Sand-hills heaped up by the action of wind on drifting sand come under the same category.

Hills of circum-detrition are such as have been left by the removal of the surrounding rocks, or are isolated by valleys of erosion.

Hills of upheaval are those formed by the elevation of a central axis faster than it can be worn down by detritive agencies.

CHAPTER V.

THE ORIGIN OF LAKES.

THE origin of the hollows or troughs in which water accumulates to form lakes has long engaged the attention of geologists, and it is now generally recognized that such hollows have been formed in many different ways. In the first place lakes may be divided into three different classes, according to their position in relation to the larger physical features of the country, as follows:—

I. Plain and Plateau lakes.
II. Valley lakes.
III. Crater lakes.

In the first class may be placed all those lakes, whether large or small, which do not lie in the course of a definite and continuous valley. In the second, those which do lie in such a valley. These two classes include by far the larger number of lakes which exist, for the third class only includes those which lie in the craters of extinct volcanoes, and the origin of these being obvious, we need not further consider them.

I. Plain and Plateau Lakes.—There are at least three ways in which such lakes may have been formed; the hollows in which they lie may be due to: (1) original irregularity of the surface; (2) unequal elevation; (3) subsidence from solution of underlying rock.

1. *Original Irregularity of Surface.*—We know that the sea-floors of the present day are by no means regular slopes or plains, but exhibit ridges and reefs, hollows and troughs, of various sizes and shapes. Some of these are probably ancient hollows formed when the sea-floor was a

land surface, and not yet filled up; but many are simply due to the action of currents and to the unequal deposition of material. When the sea-bottom is again raised into land some of these hollows will be occupied by fresh water and will become lakes.

Unequal surfaces of deposition are specially characteristic of deposits laid down by the agency of ice, whether land-ice or sea-ice; deposits so formed always present an irregular hummocky surface, in the hollows of which water naturally accumulates when the surface again becomes dry land. Such surfaces are common all over the northern parts of Europe and North America.

Lakes occupying hollows which have once been portions of sea-floors are not infrequent. Thus there is good reason to believe that the whole of Central Asia was once a sea comparable to the Mediterranean, the lakes both salt and fresh which now exist there being merely the deeper portions of that sea, for the creatures which live in them are chiefly marine types. Crustacea belonging to marine genera also exist in Lake Wener (Sweden), in Lake Superior, and even in Lake Titicaca (Peru). The last is 12,500 feet above the sea, but several species of a small Crustacean called *Allorchestes* occur in it, one of which is identical with a form still living in the Straits of Magellan. In all these cases the conclusion has been drawn that they were hollows filled originally with sea-water, which has been so gradually replaced by fresh water during the elevation of the country that some of the marine creatures were able to accommodate themselves to the change of conditions.

2. *Unequal Elevation.*—No part of the earth's surface seems to have been stationary for a very long period of time, speaking in a geological sense, and as movements of upheaval or subsidence affect limited areas, it often happens that elevation is proceeding in one area while a neighbouring area is stationary or sinking; consequently if the two areas form part of one continental region, the surface of this region is being slowly tilted. Such a tilt may only increase the original slopes, but on the other hand it may have a contrary effect, and may even reverse the slope of the lower and more level parts of the region.

It is obvious that in such a case the whole drainage of the country will be altered, and lakes are likely to be formed during the process.

It has recently been suggested by Mr. H. H. Howorth that such a reversal of the drainage and general slope of the country has taken place in Northern Asia.[1] He thinks that when the Mammoth lived in Siberia part of the Polar Sea was land, and the Siberian rivers flowed southward into the Central Asian Sea mentioned above; the present arrangement being a reversal of the drainage consequent upon the elevation of the central plateaux and the subsidence of the Arctic part of Asia. If this view is correct some of the Siberian lakes may have been formed during this gradual change of slope.

3. *Unequal Weathering*—It was stated in Part I., Chapter VI., that in the process of weathering or disintegration by atmospheric agencies some rocks were decomposed to a great depth. This is especially the case with coarse felspathic rocks, like Granite, Syenite, and Gneiss; and Pumpelly has called attention to the fact that where such rocks have been exposed to this weathering process for a long time incipient rock-basins are formed. He points out that the surface of the solid rock below the decomposed portions is very irregular, here rising into mounds and ridges, there falling into hollows and troughs, according as the rain-water has been directed toward certain places and along certain lines, and as its action has been helped by the presence or absence of vegetation, or by differences in the durability of the rock itself. It is clear, therefore, that if the loose and decomposed parts of such rock were removed by any detersive agency the underlying depressions might eventually be converted into lakes. He specially indicates certain enclosed basins in crystalline rocks in Asia as having been formed by the unequal decay of the rock and the removal of the residual materials by the wind.[2]

In the northern parts of both hemispheres there are large tracts of granite and gneissic rock, and before the

[1] "Geol. Mag.," Dec. 3, vol. vii. (1890), pp. 5 and 438.
[2] "Amer. Journ. Science," third series, vol. xvii. p. 139.

advent of the Glacial period or Great Ice Age, of which mention was made on p. 155, all these surfaces must have been more or less weathered in the manner described. During that period many of these tracts were swept by enormous glaciers and sheets of ice, and the higher portions of them were left in the condition of bare rocky surfaces smoothed and rounded by the passage of ice, all the loose rock and soil having been carried down to lower levels. These rocky surfaces are now covered with lakes and tarns, lying not only in the course of the valleys, but scattered on the slopes of hills and on the backs of broad ridges.

Such rock-tarns have been attributed by Sir A. Ramsay and other geologists to the direct action of ice, without due consideration of the probable previous condition of the surface, and ice has consequently been credited with a power of excavation far in excess of that which it really possesses. No one can doubt that the present surface of these districts has been swept and modelled by land-ice, but it does not follow that the hollows or rock-basins in which the lakes lie were actually formed by the ice. In the author's opinion the hollows, or most of them, were pre-existent, though filled with deposits or with decomposed rock; the ice only acted as a denudant, using that term in its proper sense of laying bare a previously formed surface: it was not the chisel which formed the surface, but only the rasper which has scraped it clean. To this point we shall recur in the sequel. We are now dealing only with those lakes which do not lie in valleys.

The extraordinary number of such lakes and tarns in certain parts of Scotland and Scandinavia ought to have suggested that some previous agency had been at work. We have Sir A. Geikie's testimony that in the north-west of Scotland "the surface of the Archæan gneiss is so thickly sprinkled with them that many tracts consist almost as much of water as of land," and in illustration he gives a map of part of the island of Lewis,[1] remarking also that the tarns occur not only in the lines of drainage, but are, as it were, scattered broadcast over the land.

[1] "Scenery of Scotland," second edition, p. 240.

Their extraordinary abundance ceases, however, to be so surprising if we realize the kind of surface which would be left on the removal of all loose and rotten rock from a district composed of gneiss.

4. *Local Solution of Rock.*—There are two kinds of rock which are eminently soluble in water, namely, Rock-salt and Limestone, the former not even requiring the presence of acids. Lakes are common in all regions where either of these rocks occupy much space, whether at or below the surface. Small lakes are known to have been formed in Cheshire by the sinking in of the surface at certain localities in consequence of the abstraction of the rock-salt below.

The solution of limestones and the formation of caverns by underground waters has been described on p. 117, and the occasional falling in of subterranean watercourses was also mentioned. Such falling in is especially likely to occur where a swallow-hole or line of swallow-holes has been established above a cavern, and when the roof has given way an open cavity of considerable size may be left. So long as the water running into it has a free exit this would not form a lake; but if the level of the country was subsequently lowered, so that the water-level in the limestone was raised, and the free drainage impeded, lakes might be formed in such cavities, and indeed in any part of the limestone area which lay below the new water-level, and the hollow once occupied by water would certainly be enlarged by surface solution, especially where water from peat-bogs drained into it. Such is probably the origin of most of the lakes in the limestone districts of Ireland.

II. **Valley Lakes.**—The greater number of lakes, and especially of smaller lakes, lie within valleys, but it is impossible to attribute the formation of such lake-basins to the agent which has excavated the valleys, namely, running water; nor can we suppose that every such basin is the site of a local subsidence. The following are the chief causes which have contributed to the formation of valley-lakes.

1. *Deformation of Valley-floors.*—During the formation of a mountain chain the successive applications of lateral pressure to the flanks of the chain may cause anticlinal

uplifts across the previously-formed valleys. We have seen that in many cases such uplifts are so gradual that the streams have time to cut through them; but if the uplift was more rapid, or if it produced a fault-cliff, or if it occurred where the valley-slope was already very slight, it might give rise to the formation of a lake, for every such anticlinal ridge has its corresponding synclinal trough behind it, and the lake would of course be formed in the trough. Besides the lateral or longitudinal flexures, cross flexures are often produced during the earth-movements concerned in the uplift of a mountain range, and these flexures will be transverse to the longitudinal valleys, tending to the formation of lakes in such valleys.

Professor Bonney considers that all the larger Alpine lakes have been originated by such flexures,[1] and his arguments have never been answered by those who ascribe them to the action of ice.

Again, mountain chains may be said to have their youth, prime, and old age, and certain districts of ancient rocks may be regarded as the worn-down stumps of old mountain chains. The valleys of such ancient ranges may, in the course of ages, have been so bent and deformed by the numerous subsidences and upheavals they have experienced, that on their final upheaval to form part of the present surface they ceased to form effective lines of drainage, becoming merely long troughs in the midst of a mountain region, with uneven floors, in the hollows of which lakes are formed. The Great Glen which traverses Scotland from Loch Linnhe to Moray Firth, and which contains Loch Ness and Loch Locky, is a valley-like trough which could not be formed under existing geographical conditions: it is doubtless a fragment of a very old valley system established when the Highlands formed part of a great mountain range that extended from Ireland to Norway, and bordered a North European continent. It appears to be part of a longitudinal valley, and its original slope was probably to the north-west; but its floor has been faulted, flexed, and distorted in various ways and at various periods.

[1] "Quart. Journ. Geol. Soc.," vol. xxix. p. 383, and xxx. p. 419.

Many other Scotch lochs may safely be ascribed to the deformation of ancient valleys, and the fact that *rock-basin lakes, i.e.*, lakes entirely enclosed by hard rocks, are most abundant on those parts of the earth's surface which consist of the older rocks, is a confirmation of the view that some of them are due to the accumulated effects of flexures and earth-movements.

2. *Subsidence from Solution.*—The formation of lake basins in this manner has already been described, and it is obvious that such hollows are just as likely to be formed in the valleys as on the plains of a limestone or salt rock district. Dr. Irving informs me that the extent to which the present Alpine valleys are underlain by beds of gypsum and rock-salt is shown by a series of models exhibited in the Geol. Reichsamtalt, in Vienna.

Dr. Credner mentions the case of the Visp-Thal, in Canton Wallis, where a series of landslips accompanied by small earthquakes continued for a whole month in the year 1855, and were caused by the undermining of the valley by the removal of gypsum in solution. The district contains twenty gypsiferous springs, and one of these alone brings up over 200 cubic metres of calcium sulphate per annum.

3. *Blocking of Valleys by Landslips.*—That lakes have frequently been produced in this way has been mentioned on p. 122. The lake of Derborence is known to have been formed by huge falls of rock from the peaks of the Diablerets (Bernese Alps), which blocked the course of the river Licerne.

Lake Alleghe, in South Tyrol, was formed by a landslide from Monte Pizzo in 1771 which heaped itself across the valley below, and barred the course of the stream. The Lago Nuovo, near Primiero, in South Tyrol, is another instance, the fall of rock coming from the Cima d'Asta on the western side of the valley.[1]

The lakes produced by the landslips which fell during the Calabrian earthquakes of 1733 have been mentioned on p. 56; and evidences of the former existence of lakes may be seen behind several of the more ancient landslips in the Alps, that at Flims, for instance.

[1] "The Dolomite Mountains," by Gilbert and Churchill, p. 451.

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It is not always easy to ascertain whether a lake is a rock-basin, or wholly or partially upheld by a moraine dam. Thus Lake Constance (the Boden See) was regarded by Ramsay as a rock-basin, but it has recently been ascertained that there is a mass of glacial detritus beneath the town of Constance, and that in all probability the lake-bottom is a moraine-blocked valley, or at any rate that the moraine helps to hold up the water. The Achensee in North Tyrol is another curious case; here the pre-glacial valley has been completely blocked by the glacial débris which has been brought down a lateral valley, and now forms the pass of Maurach at the south end of the lake, only about 40 feet above its surface. This accumulation is believed to have reversed the drainage, the present outlet of the lake being at the north end, while the ancient stream flowed southward through the Jenbach gorge into the river Inn.[1]

5. *Erosion of Rock-basins by Ice.*—Sir A. Ramsay's theory, that many lake-basins have been actually excavated out of solid rock by ancient glaciers, has been previously mentioned (see p. 159 and p. 624), and it was stated that the arguments by which the theory was supported cannot be regarded as conclusive. The case for the agency of ice could not be put better than in the cautious and guarded words of Sir A. Geikie, who says "that glaciers have occupied the glens where these lakes exist, and have worn down the rocks along the sides and bottom of the cavities, cannot be doubted; but whether the ice would be capable by itself of eroding hollows so deep as many of these lakes is a question which has been answered with equal confidence affirmatively and negatively." He thinks it proved that "to some extent at least the rock-basins [of glen-lakes] have certainly been eroded by ice," and that when all the circumstances of their position are considered, "one cannot but feel, though the problem is not wholly solved, that rock-basins are inseparably interwoven with the glaciation of the regions in which they occur."[2] With these remarks, so far as they refer to the deepening of glen-lakes,

[1] See Penck, "Glaciation of the Northern Alps."
[2] "Scenery of Scotland," second edition, 1887, pp. 231-234.

everyone can agree, and it is also quite possible, as he suggests on a later page, that in a valley which traverses an alternating series of hard and soft rocks, the glacier which occupied it may have worn down the soft rocks below the level of the channel made by the stream it displaced, and under such conditions may have actually have excavated a shallow rock-basin.

While, therefore, it may be admitted that under very favourable circumstances a glacier may, perhaps, have originated a shallow rock-basin, there can be no doubt that Sir A. Ramsay pressed his theory too far. It is generally admitted that in confined valleys glaciers are powerful detrusive agents, and are quite capable of sweeping out any loose detritus or decomposed rock which lies in their path, and this is quite sufficient to account for the phenomena presented by areas where lakes abound. In every country the pre-glacial surface must have supported many lake-basins of ancient date, which were more or less filled with sediment, and also many tracts of rock which had been deeply but unevenly weathered; all these would be cleared out by the glaciers as they increased in size and weight, and when the ice-age had passed away they would be left as clean-swept basins and depressions bearing all the well-known marks of the passage of ice. As already mentioned, this seems to have been the history of most of the lakes and tarns that abound in glaciated regions.

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NOTE.—It has recently been ~~shown~~ by Dr. J. W. Spencer that the great lakes of North America owe their origin in the first instance to the blocking of ancient valleys by Boulder-clay; but that their present levels and contours are due to a subsequent unequal elevation of the region, the uplift being greater to the north-east. Dr. Spencer thinks that Lake Erie was formed entirely by this differential uplift.[1]

[1] See "Quart. Journ. Geol. Soc.," vol. xlvi. p. 523, and "Geol. Mag.," 1891, p. 262.

CHAPTER VI.

THE FORMATION OF CONTINENTS AND MOUNTAIN CHAINS.

HAVING in the previous chapters explained how the surface of the land is sculptured into hill and valley, peak and pass, we may conclude by approaching a more difficult subject, namely, the manner in which the continents themselves, and the mountain chains which form part of them, have been raised into their present positions. This will take us out of the sphere of observational geology and carry us into the realm of speculative science, where conclusions can only be regarded as matters of fair probability.

General Form of Continents.—Let us, in the first place, glance at the general arrangement of the larger features of the earth's surface. It is well known that nearly three-fourths of this surface are depressed below the rest, and are covered by salt water. These depressions are called *Oceanic basins*, and the intervening areas of dry land are termed *Continents* or *Continental plateaux*. Certain portions of the continents rise to a still greater elevation, and form long ridges or *mountain chains*.

It has been pointed out by Professor Dana and others that the arrangement and relative position of oceans, continents, and mountain chains is peculiar and significant. The facts may be stated as follows, and may guide us in considering the probable origin of these great features.

1. Mountain ranges are chiefly developed along the borders of continents, and enclose basin or trough-shaped areas.

2. The highest mountain ranges face the deepest parts of the oceans.

3. All mountain ranges are formed of rocks which have been subjected to enormous lateral compression.

In support of the first proposition we may take a brief glance at the larger surface-features of the great continents.

North America has the ranges of the Rocky Mountains and Sierra Nevada on the west, the Alleghany range on the east, with the great plains of the Mississippi basin between them.

South America has the great chain of the Andes all along its western border, the Brazilian ranges on the east, and other mountains along the northern border, while the central portion consists of low plains traversed by great rivers. A transverse section across the centre of this continent, from Chili to Parana in South Brazil, would appear as in fig. 213.

Fig. 213. Diagrammatic Section through South America. *a*, Andes. *b*, Brazilian highlands.

Africa has ranges of mountains parallel to all its coasts. The interior of the southern half of the continent consists of vast plains, with an elevation of from 3,000 to 4,000 feet above the sea, and bounded on all sides by mountain chains. The northern half is of similar construction, but the average level of the Sahara desert is much less, and large parts of it are between 100 and 500 feet above the sea.

The Europasian continent does not present such regularly disposed ranges of mountains. Nevertheless we find the Scandinavian chain on the north-western border, and a succession of lofty ranges traversing its southern regions—viz., the Pyrenees, Alps, Balkans, Caucasus, Hindoo-Koosh, and Himalayas. The northern part of the continent presents a series of great plains which nowhere rise to more than 2,000 feet above the sea except in the Oural Mountains and in the Scandinavian range.

Australia consists chiefly of plains of low elevation, with

a range of mountains along its eastern border, a lesser range of hills on the west side, and a central swell which reaches to between 3,000 and 4,000 feet above the sea.

The second statement, that the deeper parts of the oceans are fronted by high mountain ranges, is supported by the following facts:—

The Pacific is at once the largest and the deepest ocean; the northern part of it has an average depth of about 3,000 fathoms, or 18,000 feet, and the southern part one of about 13,200 feet. It is surrounded by a nearly continuous set of mountain chains: on its eastern side are the Andes and the Rocky Mountains, the former including some of the highest summits in the world, and the average height of its crests being about 12,000 feet. The average height of the Rocky Mountain crests is about 10,000 feet; and the ocean outside both plunges rapidly down to over 12,000 feet, so the total average height of the slope is from 22,000 to 24,000 feet.

The mountains of eastern Asia do not rise to such great heights above the sea as those of America, but there is good reason to regard Kamskatka and the Japanese Islands as parts of a submerged mountain chain; it is remarkable that immediately outside these islands there is a long tract where the ocean is over 4,000 fathoms deep, so that the slope from the ocean depths up to the Asiatic plateaux is about 26,000 feet high. The Philippines, New Guinea, and eastern Australia, seem to form a continuation of this submerged range; they contain mountains which rise into peaks of 7,000 to 13,000 feet, while the ocean outside them sinks to about 2,000 feet.

The Atlantic Ocean is the next in size; it is divided longitudinally by a ridge over which the average depth of water is only 1,500 fathoms, while on each side it sinks into troughs which have a mean depth of 2,500 fathoms. The mountain ranges around it, however, are comparatively low. The Brazilian highlands reach to about 6,000 feet, the Appalachians to about the same height, and the average height of the West African ranges is from 5,000 to 7,000 feet. The slopes from the Atlantic troughs up to these mountain ranges have consequently an average height of 21,000 feet, notwithstanding the low height of the ranges.

The Indian Ocean has an average depth of about 2,200 fathoms, or 13,200 feet. It is bordered on the west by the high ranges of East Africa, which have an average height of 6,000 to 8,000 feet; it is faced on the north (India only intervening) by the largest area of lofty land in the world, the great plateau of Central Asia, with the range of the Himalayas, of which the average crest height is nearly 15,000 feet. On the north-east is the Malay Peninsula and Archipelago, apparently a submerged range, but many peaks of which still rise to 12,000 feet, while the ocean near them sinks to 3,000 fathoms, or 18,000 feet.

In contrast to these high ranges and deep ocean troughs we have the Arctic Ocean, of which the average depth is only 1,000 feet, and of which large parts are less than 600 feet, these shallow waters being bordered by the low plains of Asia and Europe. It is noticeable, too, that the only deep part of this ocean is opposite the highest part of Northern Europe, namely, the Scandinavian highlands.

Summary of Facts to be accounted for.—The evidence of the third statement made on p. 632 has been given on p. 617, and the facts to be accounted for may be summed up as follows.

The great oceans are deep basins, the deepest parts of which often run parallel to the borders of the continents. The continents are high plateaux, the mean height of the land above the sea, according to Dr. J. Murray, being 2,200 feet, and 16,800 feet above the mean depth of the ocean-floor. The chief mountain ranges of the world run along the borders of the continents and face the deepest parts of the oceans; the total average height of the slopes from these ocean depths to the mean crest height of the mountain chains is from 20,000 to 26,000 feet. The structure of the mountain chains shows them to be portions of the crust which have been ridged up by lateral compression, so that they always consist of bent and contorted strata (see p. 617, and fig. 211).

Further, mountain chains appear to have roots—that is, the crust appears to be thicker beneath them than it is elsewhere. There are two considerations which lead to this conclusion: A. The fact that mountain chains attract the

plumb-line, but in a degree less than is proportionate to their visible mass. It has been calculated how much attraction ought to be attributed to the mass of the Himalayas, and it was found that they ought to have attracted the plumb-line more than they actually did. Sir G. B. Airy has explained this anomaly by the supposition that there is a still greater protuberance of rock downwards into a denser yielding substratum than there is upward into the air. B. That pointed out by Mr. O. Fisher, that the downward increment of temperature is less beneath mountains than beneath plains, as it should be if there were a greater thickness of rock beneath the former.[1]

We have now to consider the explanations which have been put forward to explain the facts above stated.

The Hypothesis of Secular Contraction.—We saw, in Part I. Chapter I., that there was good reason for believing that the earth has always been losing heat by dissipation into space. Now it has been ascertained by experiment that most rocks expand when heated, and contract when cooled; and it has been assumed that when they pass from a fluid or pasty condition into a solid crystalline state, the contraction they undergo produces a considerable diminution of their volume. Hence, it is said, that if the earth is a cooling globe, it is also a contracting globe, and that its mass has been continually shrinking in volume, so that every portion of it has been compelled to occupy less and less space.

Experiments have been made on various rocks to ascertain the actual amount of contraction they undergo in passing from a fluid to a solid state. Bischof experimented upon granite, trachyte, and basalt, and according to his results it appeared that granite contracts 25 per cent., trachyte 18 per cent., and basalt 10 per cent. Subsequent investigations, however, have thrown some doubt upon these results, and those arrived at by M. Delesse are probably nearer the mark. His experiments showed that the more acid rocks (granite, felsite, etc.) contracted more than the basic rocks (basalt, etc.), but that the amount of contraction never exceeded 10 per cent., and was more often

[1] "Physics of the Earth's Crust," pp. 152, 281.

between 3 and 7 per cent. Mr. Mallet's experiments indicate a still less amount of contraction in the case of ordinary slag. Finally, observations on Kilauea seem to show that solidified basic lava is less dense than the liquid magma from which it has crystallized, for crust-like masses sometimes form and float on the top of the pools in the crater. It may be, therefore, that it is only the highly silicated rocks which contract on cooling.

We may, however, assume that the continual dissipation of heat has caused a certain gradual contraction of the earth's mass. The materials of the earth conduct heat very badly; consequently the surface, being exposed to the sky, would become covered with a cooled crust, while at a very moderate depth the temperature was still very high; just as a lava stream can be walked over while it is still molten inside. The circumference of the crust so formed would be that of the hotter globe. As time went on, the heat from within would pass out through the cooled crust, and this would be accompanied by a shrinking of the interior. But the outside of the crust was cooled while the globe was larger, and although it will have grown thicker, still it will remain too large for the shrunken interior, upon which, therefore, it will settle down by its own weight.

It is impossible, however, that there could be any disseverance or break of continuity between the outer and inner portions of the contracting globe, for no part of the earth's crust could stand without support from below: the power of gravitation (or the weight of its own mass) must crush in the outer layers of the crust and force it to accommodate itself to the diminishing circumference of the contracting interior.

It requires only an elementary knowledge of mechanical principles to perceive that the inward pressure of a rigid arched envelope or crust must necessarily be accompanied by enormous lateral pressure. If the interior of the globe is drawing away from the outer crust, we may look upon the crust as subjected to vertical forces acting equally from every direction, and it is clear that these forces will be accompanied by tangential forces causing lateral pressure in every portion of the earth's crust.

This lateral pressure would produce very powerful compression and crumpling of the rocks composing that crust, resulting eventually in their bending, breaking, and ridging up along certain lines. In other words, the crust could only continue to embrace the nucleus by a process of crushing and crumpling, and this process would continue whether the interior were solid or liquid.

If, therefore, this conception of the mode in which compression of the crust has proceeded is correct, if the crust has become wrinkled and contorted in consequence of its closing in upon the shrinking interior mass of the globe, then there is no doubt that the pressure thus generated would be amply sufficient to cause elevations and depressions of the surface, and might by its repeated action develop such features as oceans, continents, and mountain chains, *if the globe contracted enough.*[1]

Objections to the Theory of Contraction.—Until quite recently there was a strong disposition among geologists to accept the hypothesis of contraction as sufficient in itself to account for the existence of continents and mountain chains. Mr. O. Fisher, however, has put the hypothesis to the proof, and comes to the conclusion that it is inadequate to account for the production of these features.[2] He admits that the great inequalities of the continental surfaces have been caused by lateral compression, but does not believe that this has arisen from the secular cooling of the earth's mass.

Mr. Fisher considers the hypothesis on two separate assumptions: first, that the earth is solid, and has cooled as a solid; second, that there is a liquid substratum below the solid crust.

[1] Mr. Fisher however, has recently shown that the amount of heat lost by the earth since the first formation of a solid crust may not have been very great. Assuming the existence of a liquid substratum, and that the crust began to be formed one hundred million years ago, which is an ample allowance for geological time, the difference between the mean temperature of the interior then and now would be only 209° F. (Appendix to "Physics of Earth's Crust," issued separately, 1891, p. 49).

[2] "Physics of the Earth's Crust," second edition, p. 121, and Appendix, p. 29.

1. On the first assumption all the inequalities produced by compression arising from contraction would be of the nature of elevations above a certain datum level. There could be no actual, but only relative, depressions, and the bottom of the ocean-basins would either coincide with this datum level or would be the parts that were least raised above it. Proceeding on this assumption, and taking the lowest parts of the ocean-floors as a base level, he estimates that the whole of the existing inequalities of the earth's surface (above the said datum level), if levelled down and spread out, would form a uniform layer of about 13,000 feet in thickness.

He then shows that it is possible to estimate the amount or volume of the inequalities which would be produced by the contraction of a cooling solid globe. In the first place it has been shown by Mr. C. Davison and Mr. Mellard Reade that in such a globe at a comparatively small depth below the surface (probably within two miles) there would be, at the present time, a layer or shell, where its material would be neither compressed nor extended; this may be called "the level of no strain." Below it the strata would be extended, above it they would be compressed. It is, therefore, entirely out of the part above this level that the surface elevations could be produced. Mr. Fisher calculates what elevations are likely to have been formed by the compression of this layer, and on the most extravagant suppositions he finds that the mean height of the elevations, if levelled down into a continuous layer, would be only a little over 6 feet. Comparing this with the 13,000 feet of actual elevation, it seems impossible that the latter could have been formed by the contraction of a cooling solid globe.

2. The second and more probable case, that there is a yielding liquid substratum, Mr. Fisher did not fully deal with in his book, but has done so in his valuable Appendix (recently issued). He finds that if the age of the world is 100 million years, and the co-efficient of contraction for liquid rock is twice as great as that of solid rock (as Mallet's experiments seem to indicate), then the depth of the level of no strain will be at present about 4 miles below the surface, and the average height of the elevations

formed by the corrugation of the material above that level would be about 44 feet. If, however, the age of the world is taken to be only 50 million of years, the depth of the level of no strain would be only about 2 miles, and the average height of the elevations only a little over 10 feet. These amounts are equally inadequate when compared with the actual average elevation of 18,000 feet above the datum level.

It has been suggested, however, by Mr. Mallet and by Professor Le Conte, that, leaving mountain ranges out of consideration, the wide continental plateaux and the intervening oceanic depressions may have resulted from differences in the amount of radial contraction, that is to say, the crust may have shrunk bodily inwards beneath the oceanic areas further than it has beneath the continental areas.

To refute this idea Mr. Fisher has calculated what the total amount of radial contraction would be. On the assumption of a solid globe whose outer crust, to a depth of 402,832 feet (a little over 76 miles), is supposed to have the conductivity made use of by Sir W. Thomson (and this limit is taken because below that depth the effects of cooling would be quite insensible), the contraction comes out as only 2 miles, with an extreme possibility of 6 miles. Now the deeper parts of the oceans are between 3 and 4 miles below the average level of the continental plateaux, and it is impossible that these depressions could be formed by excess of radial contraction if the total amount of that was only 2 miles, while if it amounted to 6 miles there is no reason why the contraction should vary so much in different places as to cause a difference of 4 miles in vertical elevation.

In the case of a liquid substratum he finds the radial contraction may have been greater; taking values for the melting temperature and the latent heat of a cooling liquid magma from experiments recently made by Professors Rücker and Roberts-Austen, and Mallet's result for the coefficient of contraction, he finds the total amount will be 6 miles if the age of the world is 50 millions of years, and 12 miles if its age is 100 millions; but the same objection remains as in the former case—no reason

can be assigned for local differences amounting to 4 miles, whatever the total amount of radial contraction may be.

Captain C. E. Dutton thinks that Mr. Fisher has touched too briefly upon another argument against the contraction hypothesis, namely, that the features to be explained are not such as would have been produced by contraction.[1] "The strains set up in the crust by a shrinking nucleus would be such that for any given amount of corrugation with the axes (of the folds) in one direction, there must be an equal amount with the axes at right angles to that direction. The localization of mountain chains and plications in long narrow belts, with the axes of the folds all approximately parallel, and with no corresponding plications at right angles to them, is an impossible result of a collapsing spherical shell." In other words, if the features were caused by contraction, there would be a network of small mountain chains all over the earth's surface, like the wrinkles on the skin of a dried apple; they would not be nearly so long or so lofty as they are.

Hypothesis of Expansion by Injections of Lava.—Mr. Fisher formerly thought that the observed phenomena of compression might be accounted for by the fissuring of the crust which results in volcanic action, the fissures opening upwards from the liquid substratum, and being filled with matter proceeding from it. Looking to the steam which is always given off during volcanic eruptions, he believes the liquid magma to contain a large amount of water-substance (dissolved in the state of gas), and thinks that all fissures originating on the under surface of the crust would be immediately filled with this gas, under a pressure of about 10,066 tons to the square foot; the gas would consequently exert this pressure in widening the fissure, that is to say, in compressing the rocks on either side of it. If the rent reached the surface, the vapour would rush forth, and be followed by the magma itself in the form of lava; if the rent did not reach the surface, the tension of the vapour in it would still gradually be diminished, and the magma would ascend higher and higher, and when

[1] "American Journ. of Science," vol. xxiii. p. 283.

solidified would form one of the dykes of igneous rock which are so frequent even in the upper part of the crust. Mr. Fisher still believes that this action supplies a cause of compression, but observes that "in all physical problems there is a danger of holding one theory of causation to the exclusion of others that are compatible with it,"[1] and he thinks the observed amount of compression requires a more extensive and energetic agency.[2]

Hypothesis of Pressure exerted by Convection Currents.—This more energetic agency he finds in the consequences likely to result from the existence of a substratum of liquid material cooling by convection. He points out that the observed movements of the crust causing upheaval and subsidence of the surface require the conditions of a thin crust resting in approximate hydrostatic equilibrium upon a yielding substratum: hence geologists cannot regard the earth as a solid globe. Further, the crust formed by cooling out of such a substratum would by this time have become thick, unless it had been prevented from thickening by the action of the substratum in constantly dissolving off, and, as it were, washing away its underside; not so fast, but nearly as fast, as it solidified. This, as has been already explained, shows that there must be convection currents in it (*op. cit.*, p. 356). Such convection implies upward and downward currents and resulting local alterations of temperature.

By making and examining successive assumptions as to the relative densities of the crust and substratum, both under the oceans and under the continents, he finds that, with the conditions that best fulfil the requirements of the problem, the convection currents are rising beneath the oceans and descending beneath the continents, so that over a certain space between them the currents will be horizontal. This flow of the liquid magma toward the conti-

[1] "Physics of the Earth's Crust," second edition, p. 295.

[2] The repeated transference of material from the interior to the surface by volcanic action would produce a certain amount of compression by causing the crust to settle down upon a contracted spherical surface, but the total compression so caused would be small, and the extravasation of lava is more likely to be a result of compression than a cause of it.

nental areas will tend to press the supernatant crust in the same direction, and to produce compression along the common boundary of the oceanic and continental areas. "As soon as compression begins to take effect, roots to the elevated portions will be produced, which, dipping into the substratum, will offer an increasing obstacle to the flow of the currents and intensify their operation" (*op. cit.*, p. 376). Owing to the lower parts of the thickened area being softened by heat, a greater thickness will be sheared downwards than upwards. Assuming that under lateral compression two-fifths of the thickened part would go up and three-fifths would go down, and that the ratio between the specific gravities of crust and substratum is the same as that between those of granite and basalt, which is nearly as that of ice to water, he shows that the thickened tract

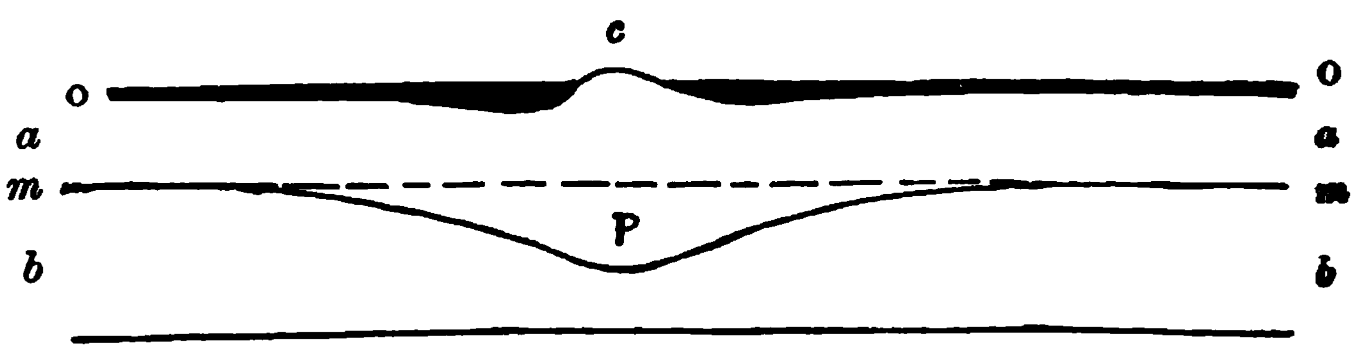


Fig. 214. Diagram to show the Roots of a Mountain Chain.

a, Crust. *b*, Substratum. *c*, Mountain chain. P, Downward protuberance. O O, Ocean level. *m m*, Lower mean level of the earth's crust.

would sag still further downwards.[1] "Hence depressions would arise on both sides of the ridge, and the ocean, which covers the general surface, would be deeper than elsewhere along two channels parallel to, and at some little distance from, the ridge. But should the ridge be steeper on one side than on the other, as seems inevitable, the ocean would be deeper on the steeper side." This relation between ocean depths and mountain chains seems actually to exist, as already mentioned.

Lastly, he considers the consequences of the transference of sediment from the mountain chains to the oceans, and

[1] *Op. cit.*, pp. 131, 278.

shows that on hydrostatic principles the areas from which matter is removed will rise, while the areas to which sediment is transported, being loaded, will sink.

Hence he concludes that the vertical movements affecting the earth's surface are of two kinds; one resulting from compression, the other from the laws of hydrostatic equilibrium simply. As the result of the latter, degradation and elevation are necessarily correlatives of each other; the degradation of the tract causes more rock to rise up, to be in its turn degraded and removed.[1]

Hypothesis of Cubical Expansion.—Mr. Mellard Reade has suggested another cause of compression and elevation.[2] He does not accept the theory of a liquid substratum, but considers that at a certain depth the material of the globe is sufficiently plastic from heat to respond to changes of pressure. This he calls the shell of greatest mobility. He points out that the deposits out of which mountain ranges have been built are always very thick, and that they seem to have been laid down in great basins, or areas of subsidence, that is to say, basins formed by the bending down of portions of the earth's crust. This bending down will locally displace the matter of the shell of greatest mobility, but at the same time (as previously shown by Babbage and Herschell) the temperature of the whole of the depressed crust will be raised.

The rise of temperature so obtained causes expansion of the rocks, and it is found by experiment that the coefficient of expansion of average rock is about 2·75 lineal feet per mile for every 100° F. of rise; but the expansion is cubical, and will be thrown into the direction of least resistance. This Mr. Reade takes to be upward, and therefore credits all the cubical expansion (*i.e.*, 8·25 feet per mile) to mountain building.

There can be little doubt that such cubical expansion does take place, and that it is an effective cause of compression, but Mr. Reade does not sufficiently consider how it may act and how far it can go. He assumes that, as soon as the depressed area of crust begins to expand, the expansion will be localized, and will bulge up the rocks in

[1] *Op. cit.*, p. 224.
[2] "The Origin of Mountain Ranges," London, 1886.

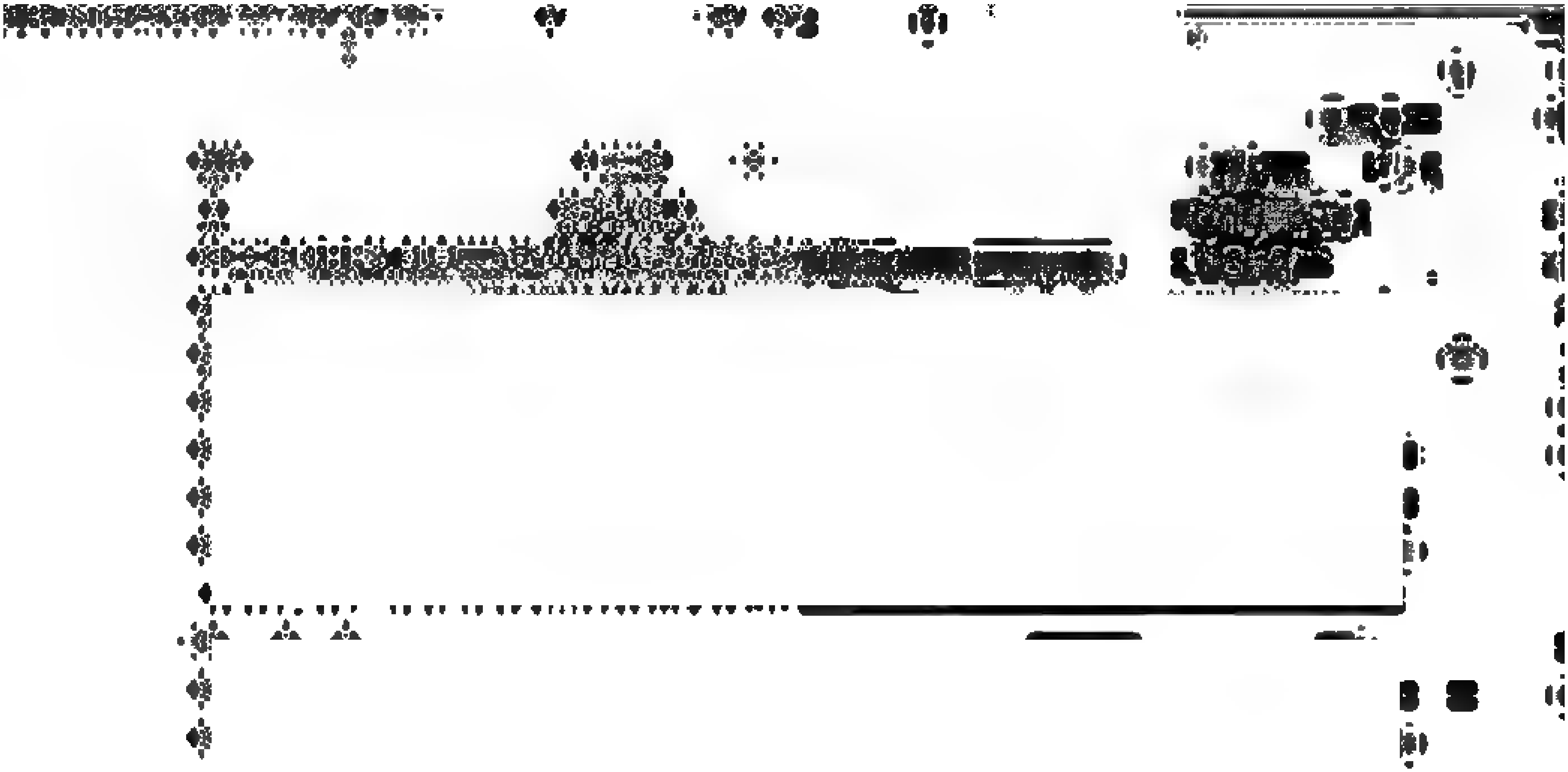
the form of a ridge parallel to the longer diameter of the depressed area. He rests this belief on the results of certain experiments on the expansion of metal plates, but as these plates were under conditions totally different from those of the earth's crust, they do not afford a sound basis for his belief.[1]

Mr. Reade admits that part of the expansion would be expended in compression and plication, and supplements his theory by supposing that the first upheaval by expansion is only the initiation of a mountain range. He thinks that this will relieve the pressure on the plastic material below, and that this, becoming liquid, will rise as lava through cracks in the crust, and by bringing fresh accessions of heat will cause further recurrent expansions of the rock-beds below the mountain range.

Summary.—If we now compare the results arrived at by Mr. Fisher and Mr. M. Reade, who have approached the same problem from very different points of view, we find that they agree in one very important point, namely, that the contraction of a cooling, *solid* globe will not account for the geological facts. They differ, however, in their conception of the condition of the interior, and, consequently, in their attempts to explain the movements of the earth's crust. Mr. Fisher refuses to be bound by Sir W. Thomson's dictum that the globe is a rigid, solid mass; he adduces weighty reasons against such a view, and in favour of the existence of a completely liquid substratum of greater or less depth; he believes this liquid magma to be saturated with gas under high pressure, and he shows how the movements of such a mobile material may exert a compressive force on the under side of portions of the crust. Mr. Reade feels more bound by the theory of effective rigidity, but he also assumes the existence of a zone of plastic material which is ready to become liquid on the relief of pressure; and he explains crust movements by changes of volume due to alterations in pressure, and a flow of the plastic material, the initial cause being sedimentation depressing a portion of the crust, which expands, and forms a surface ridge, or mountain range. To Mr. Reade's theory

[1] For a discussion of Mr. Reade's theory and other objections to it see "Geol. Mag." for January, 1892, p. 24.

there are serious objections, while the only grave objection to Mr. Fisher's is the doubtful argument from the tides; and the existence of a liquid substratum is so very probable, that it may be accepted as a sound theoretical inference from the facts which are at present known to us.



VIEW OF THE ENVIRONS OF CLERMONT FROM THE [illegible]

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